12-16-2015

From Participation to Differentiation: A Framework for Re-Designing a Socio-Technical System

Victoria Townsend
University of Windsor

From Participation to Differentiation:
A Framework for Re-Designing a Socio-Technical System

by

Victoria Townsend

A Dissertation

Submitted to the Faculty of Graduate Studies

through Industrial and Manufacturing Systems Engineering

in Partial Fulfillment of the Requirements for

the Degree of Doctor of Philosophy at the

University of Windsor

Windsor, Ontario, Canada

From Participation to Differentiation:

A Framework for Re-Designing a Socio-Technical System

by

Victoria Townsend

APPROVED BY:

Dr. Luciënne Blessing, External Examiner
Université du Luxembourg

Dr. Pierre Boulos
Department of Philosophy and Centre for Teaching and Learning

Dr. Zbigniew Pasek
Department of Industrial and Manufacturing Systems Engineering

Dr. Waguih ElMaraghy
Department of Industrial and Manufacturing Systems Engineering

Dr. R. Jill Urbanic, Advisor
Department of Mechanical, Automotive, and Materials Engineering

October 7, 2015

Declaration of co-authorship / previous publication

Co-authorship declaration

I hereby declare that this dissertation incorporates material that is result of joint research, as follows. This dissertation includes three publications that represent joint research undertaken with Dr. Jill Urbanic (Advisor), including one publication with Dr. Pierre Boulos (Outside Program Reader). These publications are outlined in further detail in the subsequent section, "Declaration of previous publication." In all cases, the key ideas, primary contributions, experimental designs, data analysis, and interpretation were performed by me, and the contribution of the co-authors was primarily through the provision of supervising on the above work, offering suggestions and feedback to improve the above work, and reviewing the above work. This is demonstrated in my first authorship of these publications.

I am aware of the University of Windsor Senate Policy on Authorship and I certify that I have properly acknowledged the contribution of other researchers to my dissertation, and have obtained written permission from each of the co-authors to include the above materials in my dissertation (as per the Approval page on the previous page).

I certify that, with the above qualification, this dissertation, and the research to which it refers, is the product of my own work.

Declaration of previous publication

This dissertation includes three original papers that have been previously published in peer-reviewed journals or conference proceedings, as follows:

Dissertation chapter	Publication citation	Publication status
Chapter 4	2014, Townsend, V., P. Boulos, and J. Urbanic, "An Ethical Roadmap for Engineering Participatory Design and Sociotechnical Participation: A Manufacturing Case Study." American Society of Mechanical Engineers 2014 International Mechanical Engineering Congress Proceedings, Montreal, QC, November 14-20, 1-8.	Published
Chapter 5	2014, Townsend, V. and J. Urbanic, "Complexity Analysis for Problem Definition in an Assemble-to-Order Process: Engaging Emic and Etic Perspectives." *Procedia CIRP* (The International Academy for Production Engineering), 17: 201-206.	Published
Chapter 9	2015, Townsend, V. and J. Urbanic, "A Case Study Measuring the Impact of a Participatory Design Intervention on System Complexity and Cycle Time in an Assemble-to-Order System," *Procedia Manufacturing*, 1: 134-145.	Published

I certify that I have obtained a written permission from the copyright owners to include the above-published materials in my dissertation (included in Appendix N). I certify that the above material describes work completed during my registration as graduate student at the University of Windsor.

I declare that, to the best of my knowledge, my dissertation does not infringe upon anyone's copyright nor violate any proprietary rights and that any ideas, techniques, quotations, or any other material from the work of other people included in my dissertation, published or otherwise, are fully acknowledged in accordance with the standard referencing practices. Furthermore, to the extent that I have included copyrighted material that surpasses the bounds of fair dealing within the meaning of the Canada Copyright Act, I certify that I have obtained a written permission from the copyright owners to include such materials in my dissertation.

I declare that this is a true copy of my dissertation, including any final revisions, as approved by my dissertation committee and the Graduate Studies office, and that this dissertation has not been submitted for a higher degree to any other University or Institution.

Abstract

Engineers are responsible for re-designing socio-technical systems (STSs). At the same time, the current literature on engineering re-design methodology is predominantly oriented towards technical artefacts. This methodology is not directly transferable to STSs, since STSs differ in the role of workers operating the system in collective activity. Accordingly, the central question of this dissertation is: How can engaging STS operators as participants in re-designing an assembly production system develop an approach for re-designing STSs that operationalizes human value and potential?

To this aim, this dissertation develops a framework for re-designing a STS. This framework is developed with design research methodology and grounded theory, modeling the re-design of an industrial assemble-to-order production system (a socio-technical system archetype) with 32 participants. The model consists of seven steps – ethical considerations for participation, emic problem analysis, emic system modeling, collective creativity, differentiated designs, emic problem evaluation, and emic system evaluation. The model and its supporting mechanisms make the following research contributions. (1) A developed roadmap of ethical considerations invites STS operators to take part in re-design with a basis of trust between researchers/engineers/designers and participants. (2) The developed investigative approaches for STS problem analysis and system modeling engage participants to define reference models and success criteria that guide the re-design process, including re-design foci. The reference models and success criteria before vs. after the re-design intervention are also compared to evaluate the re-design impact and experience, informing future re-design. (3) The developed model of OPEN collective creativity, from a co-design activity, engages participants in transforming the re-design foci into differentiated, contextualized designs. The non-linear model centralizes OPEN actions (opportunities, problems, enquiries/questions, and needs) between concept and detail ideas, integrating problem solving and inquiry with collaboration. These research contributions engage STS operators as participants in operationalizing human value across the developed model for re-designing a STS. Future research is proposed to assess the limitations of the proposed re-design framework and to examine its transferability for broader research and practice in re-designing STSs.

Dedication

This work is dedicated to my husband

Paul Mourad

for his steadfast support

Acknowledgements

Thank you to my dissertation committee – Dr. Luciënne Blessing, Dr. Waguih ElMaraghy, Dr. Zbigniew Pasek, Dr. Pierre Boulos, and Dr. Jill Urbanic. Thank you, Dr. Blessing, for your thorough and thoughtful feedback; it is an honour to have you as an external examiner, and I am very grateful. Thank you, Dr. Waguih, for our meetings and for your help in relating this research to engineering design and systems design research and practices, such as Dr. Blessing's DRM book. Thank you, Dr. Pasek, for our meetings and for encouraging me to dedicate significant time to my dissertation research, along with offering helpful references such as Vermaas et al.'s text. Thank you, Dr. Boulos, for our meetings and for teaching me about research ethics and learning, and for sitting with me when times were tough. Thank you, Dr. Urbanic, for believing in this research from the very beginning and for your encouragement and support; I am very grateful.

I owe particular gratitude to all of the participants in this research study who co-developed this research through their participation. Each participant has shaped this research and made it possible, and I am so grateful for all that you have shared and taught me. Correspondingly, I also owe a debt of gratitude to the industrial partner and, in particular, the manager with whom I worked, whose commitment to this research project and patience has been a great blessing and from whom I have learned a great deal about leadership. Although I can't name names, due to confidentiality, you know who you are. I am also grateful to all of the kind-hearted people in manufacturing with whom I have worked, who have taught me so much.

This research has been funded by the Natural Sciences and Engineering Research Council (NSERC) Engage Grant program, for which I am very grateful. To the reviewers, thank you for believing in this project. I have also been fortunate to receive funding through the Ontario Graduate Scholarship program, and I am very thankful to the government for providing this assistance, which has made pursuing a PhD possible for me.

A special thanks to all of the people at the University of Windsor who have helped me out of their generous nature, I am truly grateful. Thank you to Dr. Chris Teplovs who taught me participatory design through hands-on participation and to Ms. Bev Hamilton for introducing us. Thank you to Dr. McMurphy who sat with me to discuss this research and picture it, and who helped me to learn the qualitative side of research. Thank you to the Centre for Teaching and Learning -- Dr. Pierre Boulos, Dr. Erika Kustra, and Prof. Michael Potter -- who opened my eyes to a new world of learning, and who helped me to discover a love of inquiry.

Thank you to my fellow classmates, colleagues, and friends. I am especially grateful to you – Renata Kobe, Majeed, Jameela, and the Khan family, Corey and Lena Walsh, Sarrah Beemer, Melissa Figueroa, Victoria and Jennifer Collis, Holly Lafontaine, Kirby Wilkerson, Sandy Marshall, and so many others.

Thank you to my family. Thank you, Dad, for your encouragement and support. Thank you, Louis, for sharing your wisdom on writing and perseverance and for being such a wonderful friend. Thank you to the Mourad family as well, for all of your support and all of your nourishing Sunday dinners.

Last but not least, I owe a debt of gratitude to my husband, Paul Mourad. You have been the most supportive, patient partner through all of this work and you have always been at my side. I am forever grateful to you.

Table of contents

List of tables

List of figures

List of abbreviations and symbols

§	Section
$\mathbf{A_{ij}}$	Adjacency matrix (other versions -- $A_{interview}$, $A_{interview(all)}$, $A_{observation}$, etc.)
A	After (the design intervention)
AA	Number of assembling tasks builder A performs
AB	Number of assembling tasks builder B performs
AR	Distribution of work ratio related to the number of assembling tasks
AT	Number of assembling tasks for the final product assembly
ANOVA	Analysis of Variance
AP	Assembly process
B	Before (the design intervention)
$c(v_i)$	Centrality (of a node in a FCM)
C	Concept
cf.	Compare with (Latin *confer*)
D	Density in a FCM
Dl	Detail
DA	Number of different components that builder A handles
DB	Number of different components that builder B handles
DR	Distribution of work ratio related to the number of different components
DT	Number of different components in the final product assembly
DF	Degrees of freedom

DFA	Design for assembly
DFM	Design for manufacture
DRM	Design research methodology
E	Enquiry or question
e.g.	For example
F-value	F-value or F-statistic (signal to noise ratio)
FCM	Fuzzy cognitive map
G	Graph (in graph theory)
H_o	Null hypothesis
IA	Impact average agreement
$id(v_i)$	In-degree (of a node in a FCM)
i.e.	In other words
L	Number of Linkages in a FCM
$\mathbf{M_{ji}}$	Magnitude matrix
MS	Mean squares
N	Number of nodes in a graph (in graph theory)
n	Sample size
NAICS	North American Industry Classification System
Nd	Need
O	Opportunity
$od(v_i)$	Out-degree (of a node in a FCM)

p-value	P-value or probability value
P	Problem
PA	Number of picking tasks that builder A performs
PB	Number of picking tasks that builder B performs
PC	Pallet count variable
PR	Distribution of work ratio related to the number of picking tasks
PT	Number of picking tasks for the final product assembly
PD	Participatory design
r	Complexity ratio
REB	Research ethics board
RQ	Research question
RQ (DRM)	Research question in design research methodology phrasing
RQ (Eng)	Research question in engineering phrasing
RQ (Soc)	Research question in social science human participant research phrasing
RSA	Royal Society for the Encouragement of Arts, Manufactures, and Commerce
R-Sq	R-squared value (% of variation in Y explained by X)
S	Start of a production run
SC_a	Value of the success criteria after the re-design
SC_b	Value of the success criteria before the re-design
SC_{impact}	Value of the success criteria impact

STS	Socio-technical system
SS	Sum of squares
TA	Number of total components that builder A handles (for one final product assembly)
TB	Number of total components that builder A handles (for one final product assembly)
TR	Distribution of work ratio related to the total number of components
TT	Number of total components in the final product assembly
T-value	Test statistic for t-test
μ	Mean cycle time of archived population [minutes/assembly]
V	Number of edges (in graph theory) in Chapter 5
V	Production phase variable in Chapter 6 and Chapter 9
Vol_{max}	Maximum production volume observed
$\mathbf{W_{ji}}$	Weighted adjacency row matrix
$X\text{-}bar_{CT}$	Mean cycle time in observation set

Note: any numeric codes used within a chapter are defined within that chapter.

List of terms

Assembly "The aggregation of all processes by which various parts and sub-assemblies are built together to form a complete, geometrically designed assembly or product (such as a machine or an electronic circuit) either by an individual batch or a continuous process" (Nof, Wilhelm, and Warnecke, 1997, p. 2).

Design

Engineering design

"Design: An ability to design solutions for complex, open-ended engineering problems and to design systems, components, or processes that meet specified needs with appropriate attention to health and safety risks, applicable standards, and economic, environmental, cultural and societal considerations" (Engineers Canada, 2014, p. 13).

Design for manufacture

Design for manufacture (DFM) is "a methodology that simultaneously considers all of the design goals and constraints for products that will be manufactured… Other aspects include all the other 'design fors' or 'abilities,' for example, design for testability, quality, reliability, serviceability, style, appearance, shipping, etc. These are sometimes referred to as 'design for X' (DFX)" (Rufe, 2002, p. 159).

Design for assembly

Design for assembly (DFA) is "a component of DFM. DFA objectively evaluates the design efficiency of a product or subassembly" (Rufe, 2002, p. 159).

Design innovation (from industrial design)

"The design innovation process starts with the real – we observe and learn from the tangible factors from real-world situations. Then we try to get a full understanding of the real world by creating abstractions and conceptual models to reframe the problem in new ways. Only then do we explore new concepts in abstract terms before we evaluate them and implement them for their acceptance into the real world. This requires fluidity in our thinking between the real and the abstract" (Kumar, 2012, pp. 8–9).

"Design" in this dissertation

In general, in this dissertation, when the word "design" is used it is used with respect to the engineering design definition above. Since this dissertation extends beyond objects, to a system perspective, system's design (definition below) is also relevant to the engineering design terminology use. Since the primary concern of this dissertation is re-design, re-design (definition below) is considered in relation to the engineering design terminology and in relation to the broader sense of design innovation (design innovation definition above), which provides further context given the inter-disciplinary nature of this dissertation. When DFM or DFA are referred to in this dissertation, they are addressed by these terms. When participatory design is referred to in this dissertation (below), it is referred to specifically.

Design method "A design method is a procedure or prescription for how to solve a design problem. Usually methods are associated with particular problem types" (Dixon and Poli, 1995, pp. I–9).

Design model “The phrase ‘models of design’ can be interpreted in two different ways: models that are used in designing, such as scale models, CAD models, sketches etc.—this is henceforth referred to as ‘models in design’; and models that are used to describe or prescribe how design is or should be (carried out)—this is henceforth referred to as ‘models of design’” (Chakrabarti and Blessing, 2014b, pp. 10, 11).

Though there are many definitions for a design model, as collected and analyzed by Chakrabarti and Blessing (2014), the following definition of a design model is utilized here for its succinctness and for its ability to distinguish between design theories and models: “Sonalkar et al. (2014) follow the distinction made by Dörner (1994) who succinctly describes a theory as ‘a formulation that explains a phenomenon’, and a model as ‘an abstraction that simulates a phenomenon’” (Chakrabarti and Blessing, 2014b, p. 13).

Design theory Design theory “is an attempt to systematically bind together the knowledge we have of experiences of design practices” (Chakrabarti and Blessing, 2014a, p. 9; Vermaas, 2014, p. 48).

Emic vs. Etic “In qualitative research, the goal is to understand the situation under investigation primarily from the participants’, not the researcher’s, perspective. This is called the *emic*, or insider’s perspective, as opposed to the *etic*, or outsider’s, perspective” (Hancock and Algozzine, 2011, p. 8).

Engineering The “practice of professional engineering means any act of planning, designing, composing, evaluating, advising, reporting, directing or supervising that requires the application of engineering principles and concerns the safeguarding of life, health, property, economic interests, the public welfare or the environment, or the managing of any such act” (PEO, 2011, p. 4).

Industrial engineering

Industrial engineering is “concerned with the design, improvement and installation of *integrated* systems of people, materials, information, equipment and energy. It draws upon specialized knowledge and skill in the mathematical, physical, and social sciences *together* with the principles and methods of engineering analysis and design, to specify, predict, and evaluate the results to be obtained from such systems” (“About IIE,” 2015).

Framework A framework is a basic supporting structure of something, inclusive of a set of ideas or facts (“Definition of framework by Merriam-Webster,” 2015). Further defined, it is a “broad overview, outline, or skeleton of interlinked items which supports a particular approach to a specific objective, and serves as a guide that can be modified as required by adding or deleting items” (“What is framework?,” 2015). For the purpose of this research, a framework is considered a supporting structure of interlinked methods, models, theories, tools, etc. that serve as a guide for re-designing a socio-technical system here.

Fuzzy cognitive mapping A cognitive map is a “qualitative model of how a system operates” (Özesmi and Özesmi, 2004, p. 44), consisting of causal relationships (linkages) between concepts (causes and effects). To create a visualization of the cognitive map, first data is coded to identify relationships in the form of cause concept/linkage/effect concept. Fuzzy logic is then integrated by giving the linkage between a cause and effect a value between -1 and 1, making FCMs both qualitative and quantitative in nature. The coding is then transferred into an adjacency matrix composed of causes (rows), effects (columns), and corresponding linkage values. This adjacency matrix is then plotted as a di-graph (the visual representation of the fuzzy cognitive map), where the linkages are shown as vectors leading to and from concept (cause and effect) nodes.

Grounded theory A specific methodology developed by Glaser and Strauss (1967) "for the purpose of building theory from data" (Corbin and Strauss, 2008, p. 1).

Manufacturing "There is unfortunate confusion created by different uses of the word 'manufacturing.' Sometimes the word is used to refer to the entire product realization process; that is, to the entire spectrum of product-related activities in a firm that makes products for sale, including marketing (e.g. customer desires), design, production, sales, etc. This entire process is sometimes referred to as 'Big-M manufacturing.' But the word manufacturing is also used as a synonym for production; that is, to refer only to the portion of the product realization process that involves the actual physical realization process that involves the actual physical processing of materials and the assembly of parts. This is sometimes referred to as 'Little-m manufacturing'" (Dixon and Poli, 1995, pp. I–8). This dissertation focuses on production.

Method "Techniques and procedures for gathering and analyzing data"

(Corbin and Strauss, 2008, p. 1). E.g. an interview. In PD, Kensing and Blomberg (1998) state that, "Mathiassen (1981) has introduced useful distinctions between methods, tools, and techniques in his work on theories and methods for systems development. For Mathiassen a method has limited application areas depending on, for example, the type of organizational and technological change desired or the number of people involved. A method also provides a particular perspective on a phenomena (e.g. an organization and its needs for computer support) and is composed of a coherent collection of tools, techniques, and principles of organization" (p. 8).

Methodology In engineering design, "A methodology is a method generally applicable to a number of problem types." (Dixon and Poli, 1995, p 1–9). A methodology is "A way of thinking about and studying social phenomena" (Corbin and Strauss, 2008, p. 2). Qualitative methodology is based on Chicago Interactionism and Pragmatism, where "knowledge arises through (note the verbs) acting and interacting of self-reflective beings" (Corbin and Strauss, 2008, p. 2).

In general, a methodology is broader in meaning and application than a method. The latter part of the word, "logos" is from the Greek for 'logic of;' therefore, a research/design methodology relates to the logic associated with understanding the way in which the aims of the research/design can be researched/designed (e.g. the appropriate methods and what makes them appropriate).

Participation Genuine participation is described in the PD literature as "the fundamental transcendence of the users from being merely informants to being legitimate and acknowledged participants in the design process… inviting users to such collective discussions and reflections requires a trustful and confiding relationship between all participants" (Robertson and Simonsen, 2013, p. 5). Additionally, a research participant is "an individual whose data, or responses to interventions, stimuli, or questions by a researcher are relevant to answering a research question" (Government of Canada, 2010, p. Glossary).

Participatory design	Participatory design (PD) regards human potential highly in social interaction and engagement (Robertson and Simonsen, 2013, p. 3) and develops it through mutual learning (Robertson and Simonsen, 2013, p. 6). In participatory design, human value is operationalized by system operators in relation to the socio-technical system and with designers who facilitate the method. Different methods of PD are classified by Muller and Kuhn (1993) in terms of the degree of participant involvement. Co-design is utilized in this dissertation research, which involves socio-technical system operators directly participating in design activities *and* early in the development cycle (Muller and Kuhn, 1993). Please see Chapters 1, 3, and 7 for more information.
Qualitative analysis	Qualitative analysis is "a process of examining and interpreting data in order to elicit meaning, gain understanding, and develop empirical knowledge" (Corbin and Strauss, 2008, p. 1).
Qualitative methodology	Qualitative methodology is more than simply using qualitative data, its primary aim is to "identify issues from the perspective

of [the] study participants, and understand the meanings and interpretations that they give to behaviour, events or objects" (Hennink, Hutter, and Bailey, 2010, p. 8).

Re-design	Re-design is generally defined in relation to products. Dixon and Colton (2000) define re-design as a common design scenario "characterized by the re-working or re-use of whole or parts of previous design solutions to generate new product designs" (p. 159). Further, Deneux and Wang (2000) define re-design in terms of products that are "based on standard elements or well-mastered technology" (p. 85). In this dissertation, this definition of re-design is interpreted in a socio-technical system context with the following perspective on technology. Technology "entails far more than its individual material components. Technology involves organization, procedures, symbols, new words, equations, and most of all, a mindset" (Franklin, 1999, p. 3). As Franklin states, "The web of technology can indeed be woven differently, but even to discuss such intentional changes of pattern requires an examination of the features of the current pattern and an understanding of the origins and the purpose of the present design" (Franklin, 1999, p. 52).
Research	"An undertaking intended to extend knowledge through a disciplined inquiry or systematic investigation" (Government of Canada, 2010).
Socio-technical systems	The socio-technical system concept "was established to stress the reciprocal interrelationship between humans and machines and to foster the program of shaping both the technical and the

social conditions of work, in such a way that efficiency and humanity would not contradict each other any longer" (Ropohl, 1999, p. 1). Socio-technical systems (STSs) have a hybrid character (Vermaas et al., 2011, p. 70). Compared to a technical artefact (e.g. a product), not only do socio-technical systems have a hybrid nature "What makes socio-technical systems special is, first of all, that they have many users at any one moment, and secondly, that they involve people in two different ways, namely, not only in the role of user of the system but also in the role of operator" (Vermaas et al., 2011, p. 70). Please see Chapters 1 and 2 for more information.

Systems analysis	"A problem-solving technique that decomposes a system into its components pieces for the purpose of studying how well those component parts work and interact to accomplish their purpose" (Whitten and Bentley, 2007, p. 160)
Systems synthesis	"A complementary problem-solving technique (to systems analysis) that reassembles a system's component pieces back into a complete system – hopefully, an improved system. This may involve adding, deleting, and changing pieces relative to the original system" (Whitten and Bentley, 2007, p. 160) Note: this dissertation's perspective on system re-design includes both systems analysis and systems synthesis.

Prologue

"The influence of a vital person vitalizes, there's no doubt about it. The world without spirit is a wasteland. People have the notion of saving the world by shifting things around, changing the rules, and who's on top, and so forth. No, no! Any world is a valid world if it's alive. The thing to do is to bring life to it, and the only way to do that is to find in your own case where the life is and become alive yourself."

- Joseph Campbell (Campbell and Moyers, 1988, p. 149)

The pursuit of discovering what it means to bring the human side of engineering design and manufacturing systems to life makes me feel alive.

1 Introduction

Engineering re-design is a design practice that is generally defined in relation to products. Deneux and Wang (2000) define re-design in terms of products that are “based on standard elements or well-mastered technology” (p. 85). Dixon and Colton (2000) define re-design as a common design scenario “characterized by the re-working or re-use of whole or parts of previous design solutions to generate new product designs” (p. 159). These definitions align with a retrieval-based approach to design synthesis, which involves re-designing a technical artefact by “building on an existing design” versus “composition from scratch” (Chakrabarti, 2002, p. xiii). Though generally defined in relation to products (technical artefacts), re-design is not necessarily limited to a technical artefact domain.

Indeed, engineering re-design is also needed in the domain of socio-technical systems (STSs) -- for two primary reasons.

(1) Engineers are responsible for designing socio-technical systems and seeing the designs through over time into subsequent designs. This responsibility is described by Vermaas et al. (2011) who state: “Even though it is eminently this hybrid character – the presence of components requiring a physical description and components requiring a social description – that characterizes socio-technical systems, the designing, implementing, and maintaining of these systems remains predominantly in the hands of engineers” (p. 70).

(2) Any subsequent design to a socio-technical system occurs in relation to the existing system (present design solution), since the social aspects (e.g. learning, work culture, etc.) and integrated socio-technical aspects (e.g. work practices) make it a living system that transcends from design to design. To reject this reality in a subsequent design is to reject the significance of the social and integrated aspects of the socio-technical system; to accept this reality in a subsequent design is to accept that designing from scratch is not appropriate. To regard the socio-technical system as a living system, therefore, involves intentionally regarding subsequent designs as re-designs that build on or, rather,

build in relation to the existing socio-technical system. These two primary reasons establish that the practice of re-designing socio-technical systems is an engineering responsibility that ought to be intentionally considered for each subsequent design of a socio-technical system.

These two primary reasons are also integral to the practice of industrial engineering. The Institute of Industrial Engineers states that, "Industrial engineering is concerned with the design, improvement and installation of *integrated* systems of people, materials, information, equipment and energy. It draws upon specialized knowledge and skill in the mathematical, physical, and social sciences *together* with the principles and methods of engineering analysis and design, to specify, predict, and evaluate the results to be obtained from such systems" ("About IIE," 2015). This inter-disciplinary and integrated characterization of systems, and of industrial engineering practice to design and improve these systems, directly correlates to re-designing socio-technical systems.

At the same time, in order to re-design a socio-technical system, the practice of re-design that has been generally defined in relation to technical artefacts cannot simply be transferred to socio-technical systems – it must be re-envisioned. Engineers are faced with unique challenges and opportunities when re-designing socio-technical systems in comparison to technical artefacts:

> *… the designing, implementing, and maintaining of these [socio-technical] systems remains predominantly in the hands of engineers, who have been educated in predominantly natural-scientific ways. That is why these systems constitute a major challenge for the engineering sciences. All kinds of traditional notions about what constitutes the designing of a technical artefact, how the design process should be structured, what kind of knowledge is required and how one should assess the functioning of a designed artefact, become very problematic whenever they are literally transplanted to the context of designing socio-technical systems… The designers of such systems are confronted with the numerous aspects that are not easily or not at all describable within the traditional engineering approach, which is overwhelmingly oriented towards the natural sciences. This traditional approach and the accompanying conceptual frameworks, models and theories therefore need to be enriched with the knowledge that has been and is being developed within the domain of the social sciences* (Vermaas et al., 2011, pp. 70, 80).

In order to re-design socio-technical systems, the practice of re-design needs to at least be enriched with knowledge of socio-technical systems and at best socio-technical (inter-disciplinary) acumen.

A socio-technical system is more than just a hybrid mix of social and technical aspects. A technical artefact, e.g. a product, can be said to have a dual technical and social nature. Technical artefacts are often designed for various social and human purposes and concern people in terms of usability. In a technical system, a user may provide an input or they may be recipients of an output. In an interactive technical system, the person gives an input to the technical system and receives an output and this cycle repeats itself, even frequently. In a socio-technical system, people are entities within the system making its design deeply indebted to social and human involvement. Compared to a technical artefact, “What makes socio-technical systems special is, first of all, that they have many users at any one moment, and secondly, that they involve people in two different ways, namely, not only in the role of user of the system but also in the role of operator” (Vermaas et al., 2011, p. 70). The impact that a socio-technical system design has on the people operating it is immediate, and the impact that people within a socio-technical system have on the design and its operation is also immediate. People not only interact with the system, they fundamentally make it function from within. People are not peripheral to the system, they are inter-connected within it and to each other. Any attempt to divide people from the socio-technical system – its design, its operation, and its re-design – contradicts the socio-technical nature of fundamental interdependence between people and technology.

For this reason, it is immediately apparent that people in socio-technical systems ought to play a role in the design and re-design of these systems, since they affect, and are affected by, the socio-technical system. This is a moral argument, as well as an argument for robust design – to validate the experience of socio-technical operators in design and appreciate these operators, their human value, and their human potential. The same moral argument is made in participatory design, which is built on respect for people as purposeful beings: “we encounter the deep questions of design when we recognize that in designing tools we are designing ways of being” (Winograd and Flores, 1986, p.

xi). The same robust design argument is also made in participatory design: "Mutual learning supports the design of technology based on the logic of the practice it is intended to support. This makes the solution more robust and sustainable" (Bjerknes and Bratteteig, 1988; Robertson and Simonsen, 2013, p. 6). Mutual learning is developed in participatory design through social interaction and engagement (Robertson and Simonsen, 2013, p. 3), which also brings human values to bear on the design process and its outcomes (a concern and driver for participatory design (Iversen, Halskov, and Leong, 2012)). Democratic decision-making is another benefit of participatory design in relation to human value, a practice that has been advocated in engineering design for some time, e.g. in the Design Research Society's 1971 conference wherein Cross (1972) urged for greater participatory decision making. An appreciation for socio-technical operators and their experience can, hence, be operationalized in the re-design of socio-technical systems directly through operator participation.

Participatory design (PD) is particularly appropriate for re-designing socio-technical systems because it shares a foundation of human value and addresses complex systems broadly. Both participatory design and socio-technical systems theory are closely related through action research. Socio-technical systems theory was developed through action research, e.g. (Cherns, 1989). Participatory design was derived from action research (Spinuzzi, 2005, p. 166). In this connection, both are strongly committed to humanizing workers in design practice and its outcomes through democratic worker involvement. This is critical to the future development of socio-technical systems since Mumford (2006) identifies, in reviewing the evolution of socio-technical systems, that moving forward "The most important thing that socio-technical design can contribute is its value system. This tells us that although technology and organizational structures may change, the rights and needs of the employee must be given as high a priority as those of the non-human parts of the system" (p. 338). Participatory design provides an opportunity to mobilize human value and potential in developing a re-design approach for socio-technical systems.

Human value is manifested in participatory design practice and its outcomes through participation; the extent of participation is largely influenced by the method of participatory design. Different methods of participatory design are classified by Muller and Kuhn (1993) in terms of the degree of participant involvement. Within this classification, and in relation to socio-technical systems, co-design involves socio-technical system operators directly participating in design activities *and* early in the development cycle (Muller and Kuhn, 1993). Co-design provides broad freedom and influence in decision-making to further develop human value through direct stakeholder participation in the practice and outcomes of design, for the purposes of re-designing a socio-technical system in this research. Accordingly, this research develops re-design activities with participants through re-design practice (in participation and co-design) in a socio-technical system archetype – a manufacturing system, specifically an assembly production system.

In a non-autonomous manufacturing production system, multiple workers operate the system simultaneously – the function of the system is reliant upon collective human activity. This reality is what gave rise to the foundational body of work on socio-technical systems theory, which was developed through action research performed with the British coalmines, e.g. (Cherns, 1989). This critical relationship between socio-technical systems and manufacturing production systems has endured and is expressed in the recent manufacturing literature, e.g. managing complex socio-technical systems is said to "contribute tangibly to the sustainable development of manufacturing" (ElMaraghy, 2011). For these reasons, the manufacturing production system can be viewed as a socio-technical system archetype, which also means that re-designing it as a socio-technical system requires consideration for the critical significance of operators and collective human activity.

Within the broad spectrum of different manufacturing production systems, collective human activity is especially integral to assembly production systems, which require numerous workers in a variety of roles to work together. In today's assembly systems, "still many operations are so complex that human assembly workers are the most efficient solution. In some cases, manual operations are the only options" (Hu et al., 2011, p. 726). In the growing paradigm of mass customization (Koren, 2010), this human ability to manage the demands of product variety is especially significant. These realities converge into the present need to re-design assembly production systems, especially assemble-to-order systems, as socio-technical systems that fully recognize human value and manifest this potential with operators in collective human activity.

By grounding the development of a re-design approach in the practice of re-designing an assembly production system through participation, the re-design approach is grounded in human potential. This grounded theory (Glaser and Strauss, 1967), qualitative methodological approach is developed in conjunction with design research methodology (Blessing and Chakrabarti, 2009) to provide an inter-disciplinary perspective with systematic rigor. This research approach also conducts its inquiry through the emic (insider) perspective – the socio-technical system operator perspective. This aligns re-design practice and knowledge into co-developing a re-design approach for socio-technical systems that is grounded in the most salient feature of socio-technical systems; in doing so, the re-design approach for socio-technical systems is distinguished from the re-design of technical artefacts.

1.1 Design research problem, approach, and questions

Engineers are responsible for re-designing socio-technical systems, which ought to be intentionally considered for each subsequent design of a socio-technical system. The re-design of socio-technical systems is also central to the practice of industrial engineering. Engineering re-design approaches that have been developed for technical artefacts are not directly transferrable to socio-technical systems, due to the unique role of workers in socio-technical systems. In socio-technical systems, workers operate the system in collective activity. This is especially true for assembly production systems, which involve numerous operators working in sync and who play a critical role in managing variety in assemble-to-order systems. An approach for re-designing socio-technical systems, especially assembly production systems, needs to be developed to consider the critical significance of operators in collective human activity and operationalize human value.

To examine this central problem in design practice, participation is utilized as a vehicle of human value across a scope of re-design activities for re-designing an assemble-to-order production system. Within these re-design activities, the operationalization of human value and potential requires sense-making, taking care to mindfully integrate social and technical aspects. This sense-making involves situational awareness in relating theory and practice, which is why the empirical study of re-design in relation to an assembly production system provides a much needed basis for developing a re-design approach for socio-technical systems. This inter-connected transition from one re-design activity to the next also develops a holistic and emic (insider/participant/socio-technical system operator) view in relation to the experience of re-design with a socio-technical archetype. Through action and reflection in this experience, inter-disciplinary knowledge and practice is developed and integrated in various forms and in tandem with participation (e.g. design models, design theories, engineering design methodology, socio-technical system theory, etc.). As elaborated in subsequent chapters, these considerations are cultivated in relation to participation, problem analysis, system modeling, creativity (including collective conceptual and detail ideation in an activity), and design evaluation (problem and system analysis through reflective practice) in re-designing a socio-technical system.

In alignment with this central design research problem and approach, this dissertation research focuses on the following research questions:

Social science phrasing (human participant research)	Engineering phrasing	Design research methodology phrasing
1. How can engaging socio-technical system operators as participants in re-designing an assembly production system develop an approach for re-designing socio-technical systems that operationalizes human value and potential?	1. What is the re-design model to re-design an assembly production (socio-technical) system with stakeholder participation, human value, and human potential?	1. How can the practice of re-designing a socio-technical system with operator participation be demonstrated and defined?

Table 1: Research question 1

Research question 1 integrates the following research questions 2 and 3.

Social science phrasing (human participant research)	Engineering phrasing	Design research methodology phrasing
2. How do alternative (e.g. social science) and existing engineering design knowledge, practice, theory, methods, tools, techniques, etc. mis/align with this participatory re-design and why?	2. What are the inputs and mechanisms to re-design an assembly production (socio-technical) system with stakeholders? How do these compare to traditional engineering inputs and mechanisms?	2. What success criteria, reference models, and support are relevant to the practice of re-designing a socio-technical system with operator participation? How are the success criteria, reference models, and support developed?

Table 2: Research question 2

Social science phrasing (human participant research)	Engineering phrasing	Design research methodology phrasing
3. What opportunities, problems, and questions arise (social and technical) in relation to the participatory re-design of the assembly production (socio-technical) system and why are they significant?	3. What are the constraints, outputs, and outcomes to re-design an assembly production (socio-technical) system with stakeholders?	3. How are the success criteria and reference models evaluated for the practice of re-designing a socio-technical system with operator participation?

Table 3: Research question 3

In examining these research questions, the dissertation makes the following research contributions.

1.2 Dissertation contributions

This dissertation contributes to developing an approach for re-designing a socio-technical system with an integrated framework, which consists of new investigative approaches for building reference models of a socio-technical system and a model of collective creativity in re-design that is informed, and evaluated, by the reference models. The contributions are categorized into three areas:

I. Novel investigative approaches for building reference models of the socio-technical system for re-design from an emic perspective through participation. The developed investigative approaches are demonstrated in reference models built for the industrial re-design project at hand with participants, and they relate to the following re-design activities:

   a. Socio-technical system problem analysis from interview;
   b. Socio-technical system modeling integrating operator knowledge and practice from field study; and
   c. Socio-technical system complexity analysis from observation.

II. A model of collective creativity in a co-design ideation activity, grounded in participants' actions.

III. A re-design model and framework for socio-technical system re-design, which begins with an ethical roadmap for participation and is built across re-design activities (emic problem analysis, emic system modeling, collective creativity, differentiated designs, emic system evaluation, and emic problem evaluation).

   a. The developed roadmap of ethical considerations for participation in socio-technical system re-design relates international research ethics principles and a professional engineering code of conduct, and it is operationalized with participants in the industrial re-design project.
   b. The developed framework and model holistically interconnect re-design activities and integrate the developed investigative approaches (including methods, analytical techniques, tools, theories, etc.), re-design reference models, model of collective creativity in a co-design activity, and the ethical roadmap for participation with situational awareness in the re-design project experience.

Several of these contributions have been peer reviewed in publications outlined in this dissertation's *Declaration of co-authorship / Previous publication.* The contributions correspond to the following peer review bodies -- *Procedia CIRP* and *47th CIRP Conference on Manufacturing Systems proceedings* (contribution Ia, published); *ASME 2014 International Mechanical Engineering Conference proceedings* (contribution IIIa, published); *Procedia Manufacturing* and *43rd SME North American Manufacturing Research Conference proceedings* (contribution Ic, published); and the *2015 Qualitatives Conference* (overview, presented).

1.3 Dissertation outline

Chapter 2 begins with a literature review on the topics of, and relations between, engineering design methodology; re-design; socio-technical systems; design methods; manufacturing and assembly-related designs; and human value. The literature is evaluated and synthesized into 11 considerations that inform the design research problem, approach, and research questions in more detail. The research contributions are also specified in more detail in relation to the literature evaluation.

Chapter 3 outlines the design of the dissertation research approach and methodology, which begins with a brief overview of design research methodology. To develop various aspects within the design research methodology, additional research methodology is related -- research as inquiry and utilizing a qualitative methodology approach with grounded theory. Next, the design/research methods are discussed, namely participatory design (co-design). The industrial context and participants in the re-design study are then described. Finally, an overview of the research design is presented in a series of IDEF0 diagrams along with a chapter overview.

Chapters 4 – 10 provide evidence in relation to the research questions and design research problem. Chapters 11 and 12 synthesize this evidence, in relation to the research questions and design research problem, into discussion and conclusions.

Chapter 4 develops a roadmap of ethical considerations for participation, which provides a foundation of respect and trust upon which the developed socio-technical system re-design framework and practice is built. This chapter examines: *What* are the ethical considerations involved in the participatory re-design of a socio-technical system, in engineering research and practice? *How* can they be operationalized in an industrial re-design project?

Chapter 5 develops an emic (insider) problem analysis investigative approach in socio-technical system re-design. This chapter examines: *How* can the problem be defined in socio-technical system re-design (from an emic and etic perspective)? *What* is the re-design problem in the STS re-design project at hand?

Chapter 6 develops an emic system modeling investigative approach in socio-technical system re-design grounded in the participants' knowledge and practice of operating the socio-technical system. This chapter examines: *How* can a socio-technical system be modeled from operator participation and how does it benefit re-design? *What* is the socio-technical system model in the re-design project at hand?

Chapter 7 develops a model of collective creativity from participant action in co-designing solution variants for socio-technical system re-design. This chapter examines: *How* do participants take action to co-design solution variants in STS re-design? *How* does the model of participant action(s) in collective creativity (in co-designing solution variants in STS re-design) compare with brainstorming?

Chapter 8 provides re-designs (differentiated designs) of the assembly production system in the industrial re-design project. This chapter examines: *What* are the participants' detailed designs for the STS (assembly production system) re-design developed from collective creativity?

Chapters 9 and 10 evaluate the socio-technical system the before vs. after system and problem to examine evidence of the impact of the re-design intervention.

Chapter 9 utilizes the emic system reference model built in *Chapter 6* to analyze and compare pre- and post-observations of the socio-technical system. This chapter examines: *How* can the differentiated designs be evaluated in a before versus after socio-technical system model comparison?

Chapter 10 utilizes the emic problem reference model built in *Chapter 5* to analyze and compare pre-interview and post-survey results. This chapter examines: *How* do the participants evaluate their differentiated designs and ideas (Chapter 7 and 8) in terms of the emic problem (Chapter 5)? Also, how do they evaluate their participatory re-design experience?

Chapter 11 discusses the findings in *Chapters 4 – 10* and relates the findings to the research questions and design research problem. The findings are related to an overall model and framework for re-designing a socio-technical system. The trustworthiness and validation of the research is discussed.

Chapter 12 discusses the conclusions of the research. This includes summarizing the significance of the dissertation's primary research contribution -- a model and framework for re-designing a socio-technical system, and its constituent element contributions. Limitations and extensions of the model are discussed with proposed future work.

2 Literature review

This chapter reviews the background work framing this dissertation. The literature review begins with a summary of re-design approaches in engineering methodology (§2.1). Literature relating socio-technical systems theory to engineering design methodology and design methods is then reviewed (§2.2). Since this dissertation relates manufacturing and assembly production systems to socio-technical systems as an archetype, research on socio-technical systems theory in manufacturing-related designs is reviewed (§2.3) as well as manufacturing-specific design and re-design techniques and approaches (§2.4). Design methods that operationalize human value are then reviewed (§2.5). Finally, the socio-technical systems theory literature is summarized (§2.6). The relationships between the main topics and the chapter sections are illustrated in Figure 1.

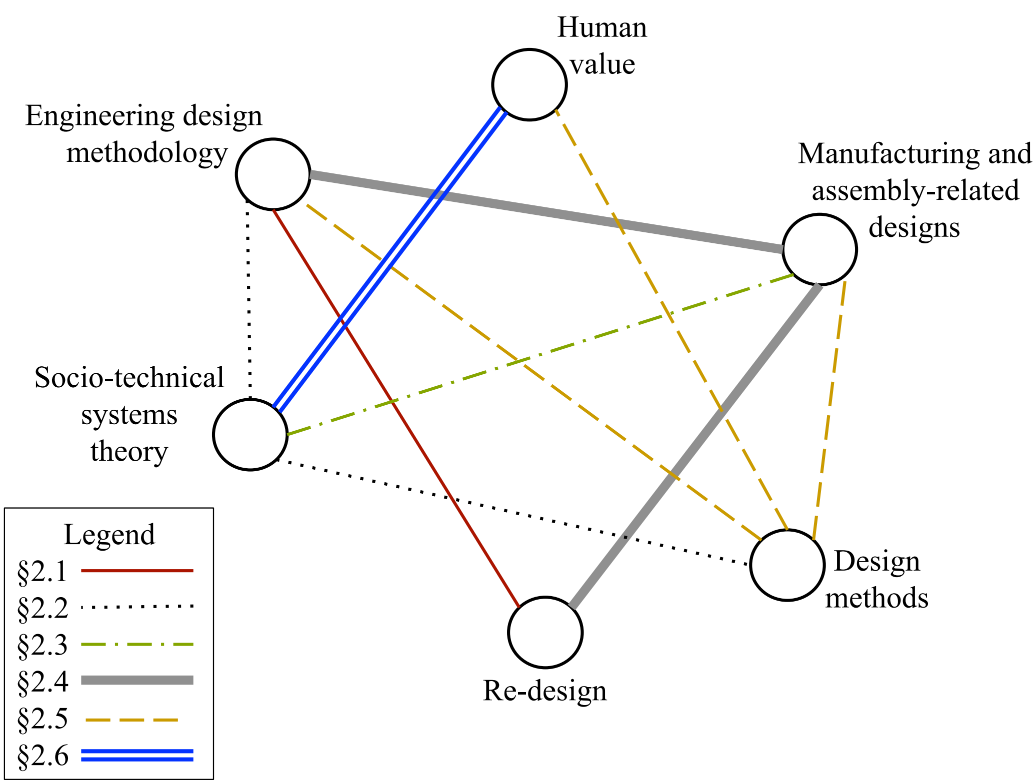


Figure 1: Relationships between the main topics in the dissertation and the literature review sections

The literature review of Figure 1 is synthesized to further inform the design research problem, approach, questions, and contributions of this dissertation (§2.7). Related work specific to a particular contribution is shared in later chapters.

2.1 Engineering re-design approaches

The literature on re-design approaches in relation to engineering design methodology is based on a number of different perspectives. These perspectives do not relate to socio-technical systems theory explicitly. A summary of this literature is presented in Table 4.

	Re-design approach (method, technique, etc.)																		Re-design application							
Citation	Re-design framework	Re-design process strategy	Re-design model	Optimization procedure	Business process re-design	Value-oriented process model	Manufacturing/cost evaluation	Knowledge-based system	Re-design through retrieval	Functional analysis	Physical representation	Focus group setting	Conceptual re-design	User-centered design	Co-design	Semantic representation	Topology	Computational synthesis	E-Supply chain integration	Computer architecture	User interface	Assembly frame	Mechanical equipment/product	Product	Electrical circuit	Socio-technical system
(Dixon and Colton, 2000)		x																					x			
(Tamura and Itoh, 1994)				x																x						
(Palma-Mendoza, Neailey, and Roy, 2014)					x														x							
(Vom Brocke, Recker, and Mendling, 2010)					x	x																				
(Sharma and Gao, 2006)							x	x															x			
(Deneux and Wang, 2000)								x		x								x				x				
(Frohlich, Lim, and Ahmed, 2014)												x	x											x		
(Van den Bergh et al., 2008)			x											x							x					
(Zendoia et al., 2013)															x	x							x			
(Murakami, 2002)									x									x					x			
(Qian, 2002)								x	x	x								x					x			
(Bhatta and Goel, 2002)									x	x								x					x			
(Faltings, 2002)									x	x								x					x			
(Finger and Rinderle, 2002)									x		x							x					x			
(Koza, 2002)									x								x	x							x	
This dissertation																										

Table 4: Summary of literature on re-design approaches

The literature in Table 4 highlights a broad range of perspectives on a re-design approach, along with research needs. The perspectives represent different degrees of granularity with respect to re-design methodology, from narrowly defined techniques (e.g. topology and physical representation) to synthesized theories and models (e.g. re-design process strategy and process models). Several of the approaches focus on computational tools for re-designing through retrieval, brought together in Chakrabarti's (2002) collection of design synthesis tools. The re-design approaches are most commonly developed and tested with technical artefacts (mechanical and electrical), though a few of the approaches relate to socio-technical aspects. Frohlich et al. (2014) identify prompts for re-designing product concepts in focus group settings. Zendoia et al. (2013) bring engineers and suppliers together to re-design machines with co-design. These examples show that the socio-technical perspective is vital to re-design, though they have not been explicitly related to socio-technical systems or its theory per se. Overall, the approaches in Table 4 highlight two re-design research needs in relation to engineering design methodology. (1) A need to integrate socio-technical systems theory into a re-design approach for socio-technical systems, to develop an approach that is cognizant of the nature of socio-technical systems and consequently fundamentally relatable to different types of socio-technical systems. (2) A need to identify, clarify, develop, and organize re-design activities across the scope of re-designing a socio-technical system.

An approach for re-designing socio-technical systems can also be related to needs expressed in recent review of engineering design research. In Chakrabarti and Blessing's (2014a) anthology of theories and models of design, they highlight several directions for future design research, including "Developing genuine system adaptation, evolution, and reproduction theories" (p. 24) with "Developing new system abstraction, modelling, prototyping, and testing theories" (p. 24). These insights are drawn in relation to Horváth's (2014) work on cyber physical systems, which are "designed and implemented in order to support human activities and well-being by decentralized cooperative problem solving, in harmony with the techno-econo-social environment" (p. 108). In other words, the need to develop and test system adaptation, evolution, and reproduction is a re-design need that is extrapolated from a socio-technical case of cyber-physical systems. This need speaks through example to the engineering need for approaches to socio-technical system re-design.

2.2 Socio-technical systems and engineering design methodology

In reviewing engineering design methodology broadly, there are a number of different perspectives that have been explicitly related to socio-technical systems theory. A relationship between socio-technical systems theory and engineering design methodology is critical if the approach is to be adopted in engineering practice. The original socio-technical systems literature includes principles for socio-technical design in relation to organizational design defined by social scientists (e.g. (Cherns, 1989a)), but how these principles can be integrated with engineering design methodology and the design activities of engineers is not discussed. This is critical to engineering understanding, especially when engineers are responsible for designing socio-technical systems, in order to relate this social science knowledge and practice to engineering knowledge and practice. Without this integration, the socio-technical scale cannot be balanced; to explain an equilibrium involves taking the inter-disciplinary perspective identified by Vermaas et al. (2011, pp. 70, 80). Without this synthesis, there is only an either/or option – the social science way or the engineering way. This dichotomy is fundamentally problematic in the face of the inter-disciplinary inherence in socio-technical systems. A summary of the literature relating socio-technical systems theory to engineering design methodology is presented in Table 5.

Citation	Knowledge representation	Co-design	Requirements analysis	Organizational design	Collaborative design	Intelligent system design	Product development	Prototyping	Computer integrated manufacturing (CIM)	Design implementation	Re-design
(Clancey, 1993)	x	x									
(Sutcliffe, 2000)			x	x							
(Appelbaum, 1997)				x							
(Lu and Cai, 2001)					x						
(Jing and Lu, 2011)					x						
(Dong, 2004)							x				
(Jones, Artikis, and Pitt, 2013)						x					
(Naumann et al., 2011)							x				
(Kember and Murray, 1988)								x			
(Panebianco and Pahl-Wostl, 2006)										x	
(Zhao, Verma, and Kapp, 1992)										x	
(Zhao and Steier, 1993)									x	x	
This dissertation											

Table 5: Summary of literature explicitly relating socio-technical systems theory to engineering design methodology

The literature in Table 5 relates to a range of design activities (e.g. requirements analysis, implementation), design methods and methodologies (e.g. co-design, collaborative design, prototyping), and design domains (e.g. CIM, organizational design, intelligent system design, product development). This literature demonstrates that socio-technical systems theory can be considered from multiple perspectives in engineering design methodology; the integration of socio-technical systems theory in the re-design of socio-technical systems is an additional perspective to engineering design methodology.

There are a number of other systems-oriented design methodologies and methods that have been influenced broadly by, but not explicitly related to, the socio-technical systems movement. Mumford (2006) provides a historical account of this. Baxter and Sommerville (2011) further contribute to this overview; a summary of their major findings with contributing authors is presented in Table 6.

Citation	Methodology								Focus					
	Soft systems methodology	Cognitive systems engineering	Computer supported cooperative work	Human-centered design	Participatory design	Ethnography	User-centered design	Empathic design	Problem solving	Complex situations/systems	Work performance	Work analysis	Human-machine interfaces/interaction	Human-machine communication
(Checkland, 1999, 2000; Checkland and Scholes, 1990)	x								x	x				
(Hollnagel and Woods, 2005; Rasmussen, Pejtersen, and Goodstein, 1994)		x								x	x	x	x	
(Suchman, 2007, 1987)			x			x								x
(IDEO, 2011)				x				x		x				
(Norman and Draper, 1986)							x						x	
(Ehn, 1988; Muller and Kuhn, 1993; Simonsen and Robertson, 2013)					x					x				
(Leonard and Rayport, 1997)								x						

Table 6: Systems-oriented design methodologies and methods that have been influenced broadly by the socio-technical systems movement (after (Baxter and Sommerville, 2011))

The summary of design methodologies and methods in Table 6 is not exhaustive; it is a snapshot of socio-technical synergy that can be utilized in conjunction with developing a socio-technical system re-design approach. For the purposes of this research, participatory design is utilized to engage socio-technical system operators directly in re-design practice to develop a re-design approach for STSs.

2.3 Socio-technical systems theory and manufacturing designs

Though the need for regarding manufacturing and assembly production systems as socio-technical systems is evident, there is a narrow body of literature that explicitly relates socio-technical systems theory to manufacturing and assembly-related designs. A summary of this literature is presented in Table 7.

Citation	Work cell design	Joint cognitive systems	Automation and process control	Automated guided vehicle systems	Control systems	Assembly system	Assemble-to-order
(Hyer, Brown, and Zimmerman, 1999)	x					x	
(Badham and Couchman, 1996)	x						
(Fraser, Harris, and Luong, 2007)	x						
(Yurtseven, Buchanan, and Basak, 2009)		x	x				
(Ottens et al., 2004)				x			
(Pilemalm et al., 2007)					x		
This dissertation							

Table 7: Socio-technical systems theory explicitly applied to manufacturing and assembly-related designs

The literature in Table 7 highlights the relevancy of regarding socio-technical systems theory concerning various types of manufacturing-related designs. Of particular note in relation to the research in this dissertation is the work by Hyer, Brown, and Zimmerman (1999), which also takes place within an assembly production system context. Their paper focuses on cell design, while the focus of the research in this dissertation addresses a broad spectrum of assembly production system aspects, relates to an assemble-to-order system, and explicitly addresses re-design -- providing additional perspectives to the body of literature in Table 7.

2.4 Manufacturing design and re-design techniques and approaches

There are several major design techniques that have been developed in relation to manufacturing and assembly systems. Agyapong-Kodua, Darlington, and Ratchev (2013) aim to integrate the most common of these techniques, with several highlighted in Table 8.

Citation	Design for manufacture	Design for assembly	Design for disassembly	Design for quality	Design for recyclability	Design for lifecycle	Design for environment	Design for safety	Design for maintainability
(Boothroyd, 1982)		x							
(Boothroyd and Alting, 1992)		x	x		x	x			
(Boothroyd and Dewhurst, 1986)		x							
(Boothroyd, Dewhurst, and Knight, 2010)	x	x							
(O'Driscoll, 2002)	x								
(Edwards, 2002)	x	x							
(Kuo, Huang, and Zhang, 2001)	x				x	x	x		
(Juran, 1992)				x					
(Deming, 2000)				x					
(Zussman, Kriwet, and Seliger, 1994)			x		x	x			
(Alting, 1995)			x		x	x			
(Fiksel and Wapman, 1994)						x	x		
(Hauschild, Jeswiet, and Alting, 2004)						x	x		
(Vujosevic et al., 1995)			x						x
(Coulibaly, Houssin, and Mutel, 2008)								x	x

Table 8: Major design techniques related to manufacturing

The techniques in Table 8 aim to improve product design by utilizing information on the manufacturing system (e.g. difficulty of assembly tasks) and its inter-related systems (e.g. impact on the environment). Several of the techniques could be said to indirectly relate to human value, e.g. by emphasizing human health through care of the environment (e.g. by considering recyclability, lifecycle, and the environment) or care in product use (e.g. by avoiding harm through safety). The techniques focus on the product or technical artefact, for which the production system serves only as a means to that end; this orientation positions the production operators in subservience to a technical artefact and subject to being perceived through a lens of human limitation (e.g. human error is mitigated to reduce scrap parts, dis/assembly tasks are simplified to improve pace and reduce part cost, etc.). An alternative is to view the production system and operators through a lens of human value and human potential and distinguish the design of production systems with meaning unto itself. The meaning of human value in the production system can then be related to, not derived from, the output of technical artefacts, products, etc. This is the design condition that Winograd and Flores (1986) identified when describing the need for participatory design, “We encounter the deep questions of design when we recognize that in designing tools we are designing ways of being” (p. xi). An approach for re-designing production systems is needed to manifest human value and potential – precisely the value orientation of socio-technical systems.

In addition to these common techniques, there are a number of other design approaches that emphasize computer technology and computational tools to design manufacturing systems and products, e.g. see summary by (ElMaraghy and ElMaraghy, 2006). In this summary, ElMaraghy and ElMaraghy (2006) emphasize that in manufacturing design research “System level synthesis, analysis, and optimization tools are required. Important aspects for the foreseeable future are advances in collaborative design tools and techniques, functional design knowledge, design synthesis, analysis and optimization, human aspects, system integration tools, design frameworks, information support systems and integration with manufacturing activities” (p. v). This very need aligns with the socio-technical systems theory emphasis on developing and connecting relationships with the “tools, techniques, devices, artifacts, methods, configurations, procedures and knowledge used by organizational members to acquire inputs, transform inputs into outputs and provide outputs or services to clients or customers” (Pasmore, 1988, pp. 55–56). This alignment positions the actions involved in socio-technical systems theory with manufacturing design research needs, and further aligns relating socio-technical systems theory into a re-design framework that is a unique and needed contribution to the manufacturing system design literature.

An additional orientation to re-design in the manufacturing literature, common in industrial engineering practice and not yet mentioned, is the Japanese approach of continuous improvement, kaizen. This approach is integral to the system of Lean manufacturing or the Toyota Production System. Kaizen is oriented towards engaging workers in incremental improvement, gradually improving the system/process through intentional iteration. This continuous improvement is based on standardization -- "When Hiroyoshi Yoshiki was hired by Toyota in Japan he was taught that standards were the basis for kaizen. If you have a standard and it is not being followed you have a problem. If you have a problem you have an opportunity to improve" (Liker and Hoseus, 2008, p. 162). Standardized work is the basis for improvement:

> *Standardized work is a concept that is often misunderstood in the concept of the lean journey. Many times we have heard the comment that standardized work is going to make a bunch of robots out of us, and take away our ability to think. Our response is on the contrary, standardized work in the Toyota culture does just the opposite. It is the baseline for improvement. The fear of becoming like a robot that we often hear in Western culture is a reflection of Western individualism. We do not want to do it like everyone else. We want to do it our way. We want to have freedom of choice on how to do the job. We want individual innovation and creativity. That is fine if the work is individually oriented* (Liker and Hoseus, 2008, p. 163).

The kaizen approach, therefore, takes the position that collective activity can only be coordinated through standardization, and standardization leads to developing hypotheses for incremental improvement. It is worthwhile to consider and explore alternative viewpoints on coordinating collective activity within socio-technical systems and on improvement, especially when considering context. The acknowledgement that standardization is contrary to western values of individualism is an important insight. In Chakrabarti and Blessing's (2014b) summary of their anthology of design theories and models, they identify that "any proposal for a model or theory should be accompanied with its purpose (what it does) and context (where it applies)" (p. 20) and "the lack of clarity of purpose and intended context of many theories and models is considered a hindrance for proper validation" (p. 24). For the purpose of this research, in developing a re-design approach for socio-technical systems with participation, the participants are in the position of developing a viewpoint on coordinating collective activity, individualism, human value, and change within a western (Canadian) context.

2.5 Design methods that operationalize human value

In addition to these manufacturing-based design methodologies, there is a broad range of methods available in human factors and ergonomics that can be used for designing and improving various human aspects in manufacturing production systems.

This field extensively covers a broad range of aspects, from designing tools, measuring work, modeling human performance, task analysis, health and safety, teamwork, psycho-social elements, etc., e.g. see (Lehto, 2013). The primary difference between human factors and participatory design methods can be drawn from the manner in which human value is operationalized, in relation to a socio-technical system here. In human factors, human value is operationalized by specialists who conduct the method in relation to the system operators and within the socio-technical system. In participatory design, human value is operationalized by system operators in relation to the socio-technical system and with designers who facilitate the method. The more general types of collaboration, such as collaborative engineering and concurrent engineering, generally operationalize human value between designers. This comparison is also visualized in Figure 2, with the participatory design method placement and classification framework adapted from Muller and Kuhn (1993).

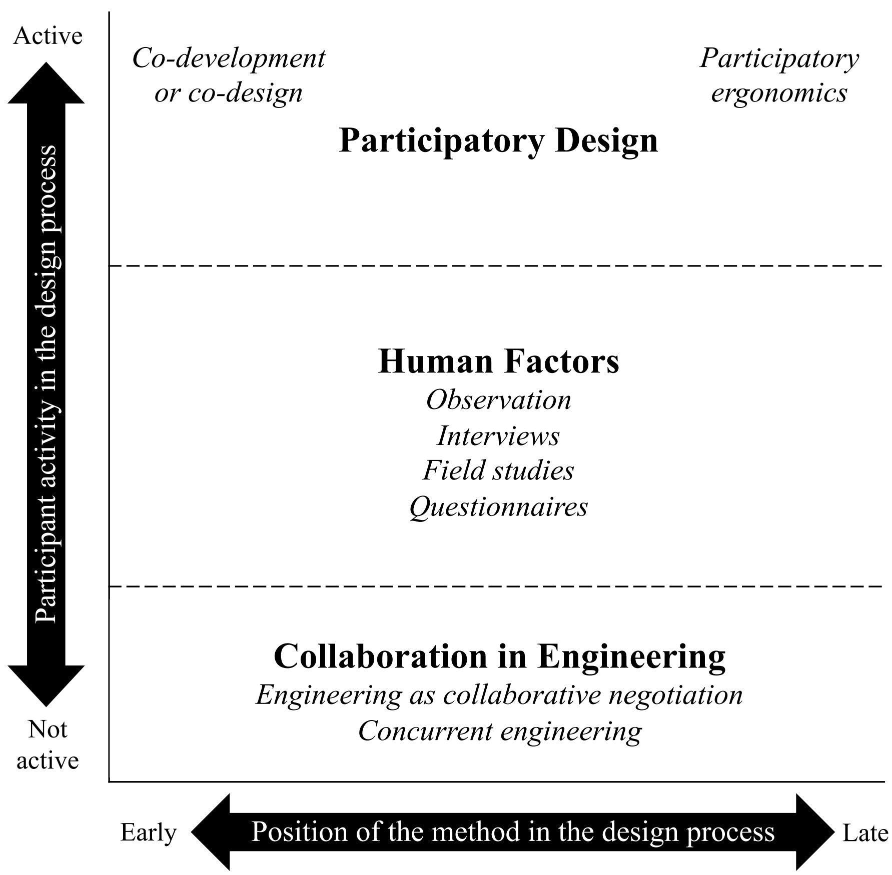


Figure 2: Classification of participatory design, human factors, and collaboration in engineering

The aim of the classification in Figure 2 is not to label some methods or approaches as ‘bad’ or ‘better.’ Rather, the aim is to understand that these different design approaches are motivated by different intents relating the x and y-axes – together here they describe the position of the socio-technical system operator participants in the re-design process, in terms of timing (x-axis) and the designer-operator relationship (y-axis). Through this categorization, it is clear that these methods differ in application via the purposes towards which they are applied in light of their impact on system operator engagement and action. For the purposes of developing an approach for re-designing a socio-technical system, common methods from human factors and co-design from participatory design are utilized; in a sense, the human factors methods act as a mechanism of sensitization between the researcher and the participants in preparation for participatory design.

Participatory design (PD) has been utilized in improving manufacturing production systems in relation to a few applications. The most common reference is to participatory ergonomics utilized to improve working conditions (Laing et al., 2005; Laing, 2007; Määttä, 2007; Sundin, 2003; Sundin, Christmanssona, and Larsson, 2004; Vink, 2006). Other applications include poka-yoke (Bonacin, Baranauskas, and Cecilia, 2003) and team organization (Rolfsen, Ingvaldsen, and Hatling, 2012). The main emphasis of this literature is thus in the latter stages of design (per Figure 2). The utilization of co-design to re-design an assembly production system adds to the applications in the manufacturing PD literature, engaging socio-technical system operators actively and early in the design process.

2.6 Socio-technical systems theory

To re-design a socio-technical system, a designer must build in relation to the existing system and ask: what are the standard elements and well-mastered technology to base a re-design on? Answers to this question can only be found by inquiring into the elements and technology in the existing socio-technical system. Technology “entails far more than its individual material components. Technology involves organization, procedures, symbols, new words, equations, and most of all, a mindset” (Franklin, 1999, p. 3). As Franklin (1999) states, “The web of technology can indeed be woven differently, but even to discuss such intentional changes of pattern requires an examination of the features of the current pattern and an understanding of the origins and the purpose of the present design" (p. 52). An understanding of the present design of a socio-technical system -- its current pattern, technology, and elements -- begins here by understanding the nature of socio-technical systems.

Socio-technical systems (STS) theory involves integrating relationships between social and technical aspects. The socio-technical system concept "was established to stress the reciprocal interrelationship between humans and machines and to foster the program of shaping both the technical and the social conditions of work, in such a way that efficiency and humanity would not contradict each other any longer" (Ropohl, 1999, p. 1). This concept is supported by STS theory that advocates that "organizational objectives are best met not by the optimization of the technical system and the adaptation of the social system to it, but by the joint optimization of the technical and the social aspects" (Cherns, 1989a, p. 3) (Cherns, 1978) based on (Emery, 1989c). The question is: How can this be embodied in re-design and in relation to engineering design methodology? In general, and from a pragmatic perspective, STS theory accomplishes socio-technical integration by developing and connecting relationships with the "tools, techniques, devices, artifacts, methods, configurations, procedures and knowledge used by organizational members to acquire inputs, transform inputs into outputs and provide outputs or services to clients or customers" (Pasmore, 1988, pp. 55–56). Socio-technical integration is also found in nine principles of STS design.

There are nine principles of socio-technical design in STS theory that relate to organizational design; incompletion (principle 9) and design and human values (principle 8) are of particular significance to this research (Cherns, 1989a; 1978). Principle 1 is compatibility, which means that the process of design must be compatible with its objectives (p. 4). Principle 2 is minimal critical specification, which involves identifying what is critical but no more (p. 5). Principle 3 is the socio-technical criterion, which involves controlling variances (a deviation that affects an outcome) nearest to their source (p. 7). Principle 4 is the multi-functional condition of an organism vs. mechanism structure that supports equifinality (p. 8). Principle 5 is boundary location, which considers how people and activities are grouped (e.g. with respect to technology) (p. 8).

Principle 6 is information flow, which aims to provide people with the information they need promptly to perform the actions that they are responsible for (p. 11). Principle 7 is support congruence, which promotes consistent behavior across an organization (e.g. reinforcement systems that are consistent with the organizational aims) (p. 12). Principle 8 is design and human values, which promotes a high quality of work (p. 12). Principle 9 is incompletion, defining design as a reiterative process (p. 13). These latter principles, 8 and 9, are addressed in this research in developing a re-design approach for socio-technical systems in support of human value.

The STS principle relating design and human values is a relationship promoted in the technology literature and related to the manufacturing literature calls for attention to human elements and socio-technical systems. Recognizing and promoting human values has been advocated broadly in various fields of technology study and articulated in different ways. These critical analyses call for regarding technology as "technique" (Ellul, 1967, 1999), as "the house of technology" (Franklin, 1999) and as social construction (e.g. (Ong, 2003)). The manufacturing literature includes similar calls to place greater importance on human elements, e.g. in the design and implementation process (Norman et al., 2002) and in the operational domain where they contribute to complexity (ElMaraghy and Urbanic, 2003). There is an opportunity to relate the calls for attention to human elements in manufacturing to the calls for human values in technology and STS theory.

The foundational relationship between STS theory and manufacturing systems identifies that work plays a critical role in relating, and integrating, social and technical aspects. The foundational STS work, performed by social scientists in the British coal mines, establishes that, "Occupational roles express the relationship between a production process and the social organization of the group. In one direction, they are related to tasks, which are related to each other; in the other, to people, who are also related to each other" (Trist and Bamforth, 1951, p. 14). Work is therefore a crux of connection between the social and technical aspects of manufacturing and assembly production systems and a means to manifest human potential in collective human activity.

In designing work as the crux between social and technical elements, STS theory identifies the need to respect people as purposeful beings. Emery (1989a) identifies that "There is an overlap in the professional interests of engineers and social scientists in the field of 'human engineering' - the design of machines and their coordinate tasks for optimum fit between them and the skills of human operators. Beyond this are problems of relating technological requirements to people as purposeful beings, not simply as another kind of machine, and to groups of people, not simply to isolated individuals" (p. 5). Respecting people as purposeful beings is, therefore, also a critical consideration for re-designing a socio-technical system and assembly production system.

To regard people as purposeful beings is an orientation that contrasts how many technological systems are structured. Franklin (1999) argues that "Many technological systems, when examined for context and overall design, are basically anti-people. People are seen as sources of problems while technology is seen as a source of solutions… the notion that maybe technology constitutes a source of problems and grievances and people might be looked upon as a source of solution has rarely entered public policy or even public consciousness" (p. 71, 73). Assembly systems are particularly susceptible to this orientation, since mass production assembly lines are a prescriptive technology that requires compliance (Franklin, 1999, p. 16) through the mechanization of pace. To regard people as purposeful beings is to challenge the prescriptive technology orientation -- to value workers for their partnership rather than compliance. Rather than viewing assembly operators as interchangeable parts, they can be viewed as unique individuals.

The reality is that manufacturing workers are not all the same and contribute to a social plurality. Canadian manufacturing workers are quite diverse, according to the 2011 Canadian National Household Survey results for the North American Industry Classification Systems (NAICS) code 31-33 for manufacturing. This survey showed that in 2011 Canadian manufacturing employees ranged from 15 to 75+, 27.8% were female and 72.2% male, and 20.7% were a visible minority who represented 34.7% of all visible minority workers in Canada (Statistics Canada, 2011). These statistics certainly argue that there is a need to regard assembly system operators as diverse individuals who contribute to a social plurality.

To integrate the different socio-technical system considerations, and relate them to re-envisioning assembly production systems, Emery has refined socio-technical systems theory into three core principles. These three core STS principles (Emery, 1989b) are outlined in Figure 3 and are further described in the subsequent paragraphs.

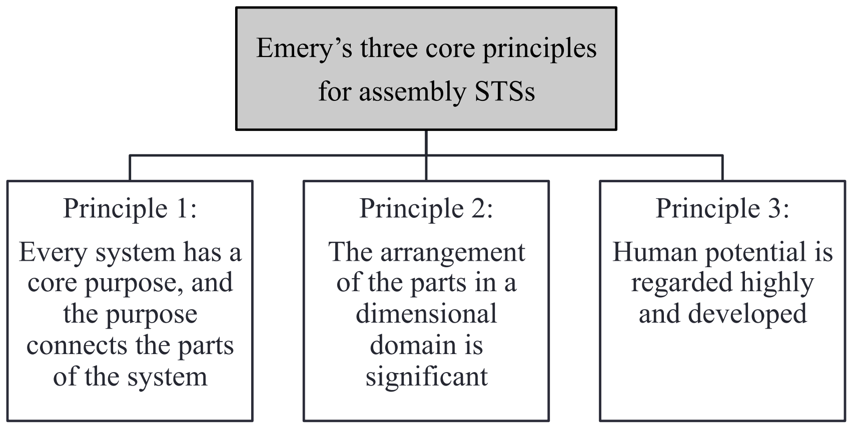


Figure 3: Emery's three core principles for re-envisioning assembly STSs (after (Emery, 1989b))

Principle 1: Every system has a core purpose, and the purpose connects the parts of the system (Emery, 1989b). Deming (2000) defined this as an "aim"; Feibleman and Friend (1978) defined this as "one controlling order"; Angyal (1972) defined this as "one and only one construction principle... unitas multiplex"; and Ackoff and Emery (2005) defined this as telos, or teleological systems. In the context of manufacturing production systems, Emery defines the purpose as: to be "economically productive" (Emery, 1989b, p. 15). This is also echoed in today's manufacturing industry, e.g. in the mission and vision statements of an over 20-year manufacturing consortium and its members' value statements that emphasize global competitiveness (Townsend and Urbanic, 2012). The core purpose, or primary function, of the assembly production system is thus considered to be economic productivity, which in its most basic form is the conversion of inputs into outputs.

Principle 2: The arrangement of the parts in a dimensional domain is significant (Emery, 1989b). Angyal (1972) notes that, "In aggregates it is significant that the parts are added; in systems, it is significant that the parts are arranged" (Emery, 1989b, p. 16). The arrangement of the parts of the system is, thus, critical to the socio-technical and assembly production system. This arrangement can be understood in relation to

Franklin's (1999) web of technology. This arrangement can also relate principle 2 and 3, through Pasmore's (1988) association between "tools, techniques, devices, artifacts, methods, configurations, procedures and knowledge used by organizational members to acquire inputs, transform inputs into outputs and provide outputs or services to clients or customers" (pp. 55-56).

Principle 3: Human potential is regarded highly and developed (Emery, 1989b). This means that, "At the simplest level, the third principle would indicate designing-in a degree of multiskilling that would meet the probable arrangements of the section about its tasks. At a more sophisticated level of design, account would be taken of the human potentialities for reasoning, creativity and leadership that might be expected in any group of 8 or 10 human beings. This would mean designing the social system of the small group so that it becomes an instrument for its members – something they largely manage themselves – not vice versa" (Emery, 1989b, p. 18). This is also emphasized by Cherns (1989a), who states that the joint optimization of the social and technical utilizes "the adaptability and innovativeness of people in attaining these goals instead of over-determining technically the manner in which these goals should be attained" (p. 3).

This socio-technical systems theory literature, and the preceding literature review, is integrated with the design research problem, approach, and questions with considerations in the following section.

2.7 Detailed design research problem, approach, questions, and contributions informed by the literature review

Engineers are responsible for re-designing socio-technical systems, which ought to be intentionally considered for each subsequent design of a socio-technical system. The re-design of socio-technical systems is also central to the practice of industrial engineering. The engineering design methodologies that have been related to socio-technical systems theory do not address the re-design of socio-technical systems (Table 5). The current re-design approaches that have been developed for technical artefacts (Table 4) are not directly transferrable to socio-technical systems, due to the unique role of workers in socio-technical systems. In socio-technical systems, workers operate the system in collective activity. This is especially true for assembly production systems, which involve numerous operators working in sync and who play a critical role in managing variety in assemble-to-order systems. Re-designing the assembly production system as a socio-technical system considers the critical significance of operators, collective human activity, and human value – a need that is not expressed in the current manufacturing-related design techniques and approaches (Table 8). An approach for re-designing socio-technical systems needs to be developed, and it would be particularly useful for re-designing assembly production systems.

In order to develop an approach for re-designing socio-technical systems, the literature review identifies the following critical considerations. An approach for re-designing a socio-technical system needs to:

(1) Ask what the standard elements or well-mastered technology are to base a socio-technical system re-design on;
(2) Be enriched with knowledge of socio-technical systems and at best socio-technical (inter-disciplinary) acumen in relation to engineering design methodology;
(3) Integrate socio-technical systems theory into a re-design approach for socio-technical systems, to develop an approach that is cognizant of the nature of socio-technical systems and consequently fundamentally relatable to different types of socio-technical systems;
(4) Identify, clarify, develop, and organize re-design activities across the scope of re-designing a socio-technical system; and
(5) Operationalize human value and potential.

The manner in which the approach for re-designing a socio-technical system is developed benefits from synergistic socio-technical methods (Table 6) and other methods that aim to operationalize human value (e.g. human factors). In human factors, human value is operationalized by specialists who conduct the method in relation to the system operators and within the socio-technical system. In participatory design, human value is operationalized by system operators in relation to the socio-technical system and with designers who facilitate the method. Both perspectives are relevant to developing an approach for re-designing a socio-technical system. For the purposes of this research, co-design, a particular form of participatory design, is selected (from Table 6) for its ability to engage socio-technical system operators in broad decision-making in re-design and fundamentally advance human value through participation. Several general human factors are also selected (e.g. field study (observation and interviews) and questionnaire) since they can also be utilized broadly and are not application-specific. Since the assembly production system is a socio-technical system archetype, and design research is fundamentally related to practice, these methods are operationalized in re-designing the assembly production system as a socio-technical system in order to develop a re-design framework.

To begin to develop considerations 2 and 3 above in the development of a framework for re-designing a socio-technical system as a whole, and in relation to an assembly production system, the following socio-technical systems theory considerations are taken into account:

(6) Align design with human values; this alignment directly connects to the technology and manufacturing literature calls for further attention to human values and human aspects in manufacturing system design and operation;

(7) Regard work as a crux to connect the social and technical aspects of the socio-technical system and means to operationalize human potential in collective human activity;

(8) Respect people as purposeful beings, which challenges the prescriptive technology orientation, and regards assembly operators as unique individuals rather than interchangeable parts of the system;

(9) Consider the core purpose of the system that connects the parts of the system -- "to be economically productive" in assembly production systems;

(10) Arrange the parts of the socio-technical system in the dimensional domain; and

(11) Regard human potential highly and develop it.

Considerations 2 and 3 also mean that it is important to integrate considerations 6-11 with considerations 1-5 in relation to the research questions (Table 1, Table 2, and Table 3) and towards developing an approach for re-designing a socio-technical system.

Accordingly, by offering socio-technical system operators the choice to participate in re-designing the assembly production (socio-technical) system, including their work (consideration 7), the co-development of a re-design framework for socio-technical systems is grounded in human potential (considerations 5 and 11) and respect for people as purposeful beings (consideration 8). This approach enables knowledge, methods, tools, techniques, etc. (consideration 1) to be applied, developed, and arranged in the dimensional domain (consideration 10) across the scope of re-design activities (consideration 4) to develop the meaning of regarding and developing human potential, value, and values (considerations 5, 6 and 11) in their own way and in context with the core purpose of the system (consideration 9).

The contributions of the dissertation – I, II, and III from §1.2 – relate to the body of literature reviewed (Figure 1) as illustrated in Figure 4.

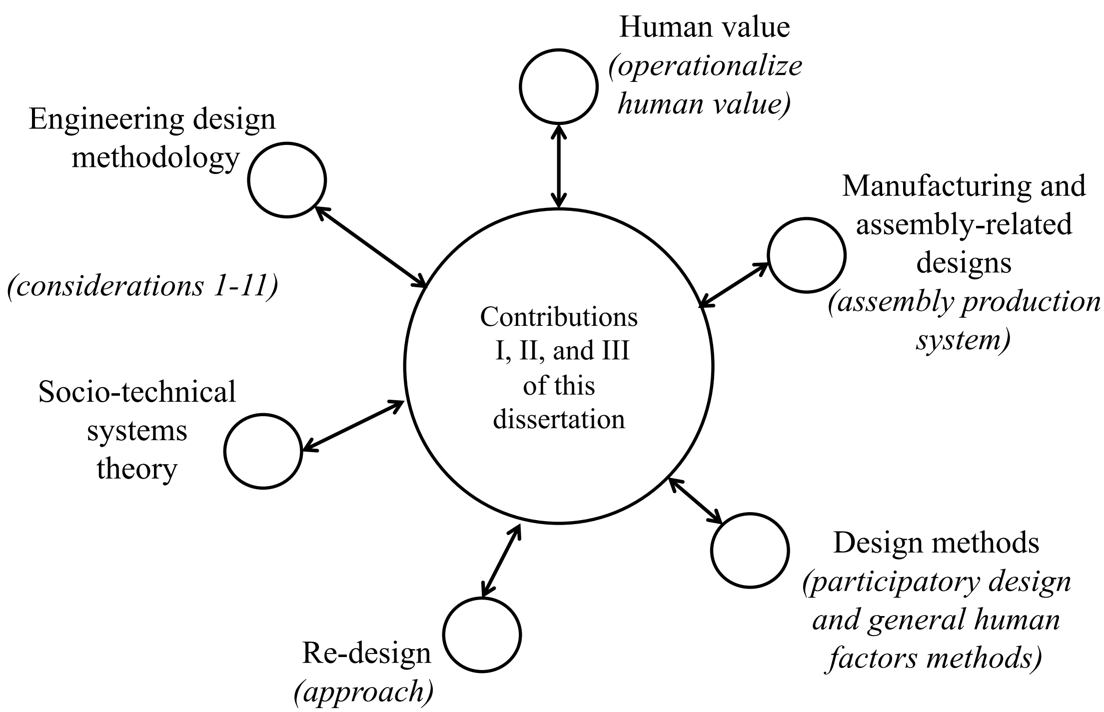


Figure 4: Contributions of the dissertation in relation to the body of literature reviewed

As shown in Figure 4, the dissertation connects the six areas reviewed – engineering design methodology; human value; manufacturing and assembly related designs; design methods, re-design, and socio-technical systems theory. In turn, the dissertation contributes to these bodies of literature and in particular highlights the integration of additional connections illustrated in Figure 5.

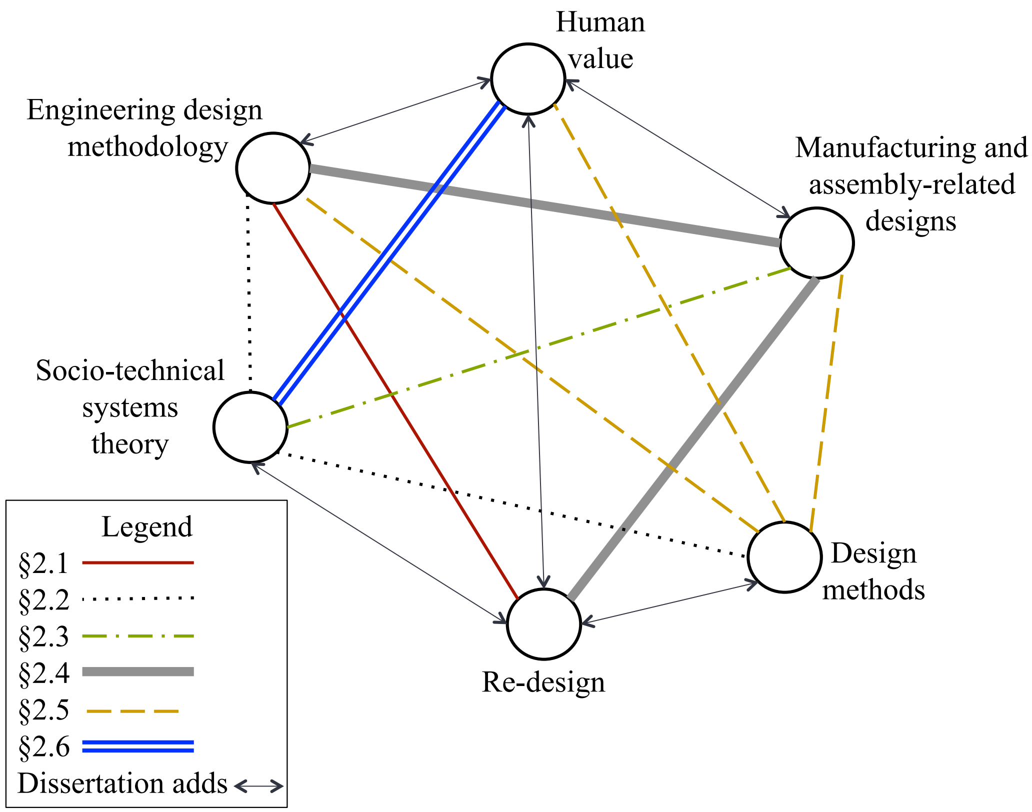


Figure 5: Added connections of the dissertation in relation to the body of literature reviewed

A detailed description of the research approach, its design and rationale, is discussed in Chapter 3.

3 Research methodology

3.1 Design research methodology

Design research methodology (DRM; (Blessing and Chakrabarti, 2009)) is a systematic approach to developing engineering design research that is flexible and accommodating to inter-disciplinary needs. The DRM approach consists of four main phases, as illustrated in Figure 6. These phases are illustrated linearly but non-linear relationships do occur and are encouraged (Blessing and Chakrabarti, 2009, p. 17). Beside each phase title in Figure 6 is an interpretation of the intent of the phase for the purposes of this research. This interpretation contextualizes and aligns DRM with taking action, the transformational orientation that is characteristic of socio-technical systems and participatory design and the modus operandi for re-design taken here.

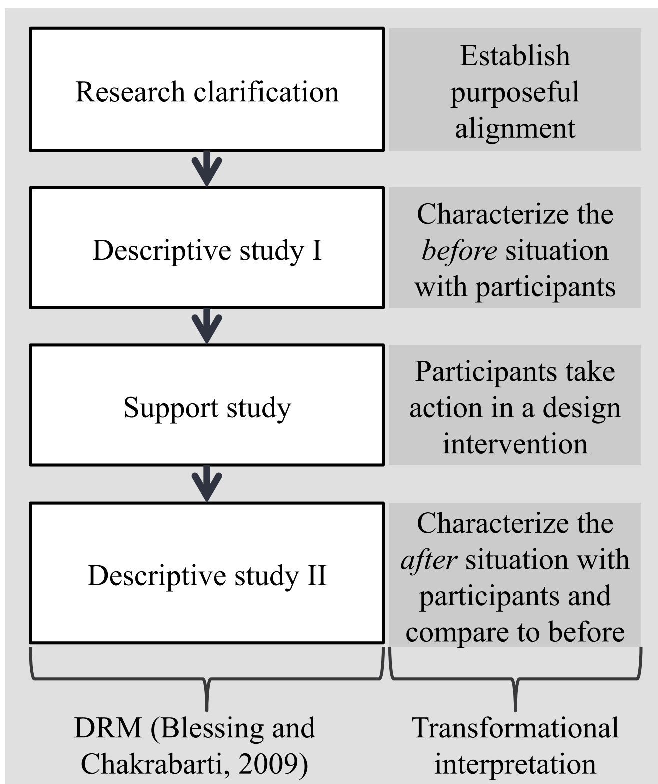


Figure 6: Design Research Methodology phases (Blessing and Chakrabarti, 2009) with a transformational interpretation

The phases in Figure 6 are outlined in more detail in the following paragraphs utilizing the DRM primary reference (Blessing and Chakrabarti, 2009). The first, second, third, and fourth paragraphs correspond to the paraphrasing of Chapters 3, 4, 5, and 6.

In phase 1 of DRM in Figure 6, the *research clarification or criteria definition* phase, the design research aims and focus for the research are identified (Blessing and Chakrabarti, 2009, p. 15). These aims and focus support the subsequent three phases of DRM in the following manner. The design research aims and focus orient the descriptive study (phase 2), wherein a more detailed account of those aims and focus are described (e.g. critical conditions, context, considerations, etc.) and form a reference model. The design research aims and focus, along with the more descriptive conditions, are utilized to inform and position intentional prescriptive or support study (phase 3), which takes form in proof of concept or a theory. The design research aims and focus also provide an alignment for the basis of comparison between the descriptive study I and II.

In phase 2 of DRM in Figure 6, the *descriptive study I* phase, a reference model is developed (Blessing and Chakrabarti, 2009, pp. 15–16). The aim is to create an understanding of the existing situation, which is similar to defining the current state as it is frequently termed in manufacturing circles. The emphasis of phase 2 is on developing a reference model that provides more clarification to the design research focus established in phase 1. Concreteness can also be built with empirical study in this phase, as is the case in this research. In this dissertation research, reference models are built with respect to studying the existing industrial situation to inform the re-design of a socio-technical (assembly production) system from a conceptual perspective and from a practice perspective in relation to the re-design industrial project.

In phase 3 of DRM in Figure 6, the *prescriptive or support study* phase, the intent is to formulate a desired design research situation using the insight from the previous two phases (Blessing and Chakrabarti, 2009, p. 16). This includes support in a range of design activities, from supporting problem definition to conceptual design. In this dissertation research, co-design takes place in phase 3 as a re-design intervention in the industrial project, in order to further discover and surface a desired re-design situation with participants; this situation is informed by the preceding phases and also supportive of the intent developed in those phases, creating a reciprocal relationship.

In phase 4 of DRM in Figure 6, the *descriptive study II* phase, the impact and support is assessed (Blessing and Chakrabarti, 2009, pp. 16–17). This evaluation is based on drawing a comparison between the intent of the support and the realization of the support in empirical terms. This can take the form of understanding applicability of the support as well as its usefulness. In this dissertation research, empirical studies are conducted in phase 4 on the situation following the re-design intervention (phase 3); the results are compared with the reference models from phase 2, wherein inferences are drawn in relation to the meaning of phase 3.

This is a brief overview of these four stages, described in relation to the dissertation research. Uses and any adaptations of DRM in this dissertation research are concerned primarily with orienting the methodology with action and transformation, e.g. viewing re-design support in terms of a participatory intervention via co-design to surface, rather than prescribe, a design situation. Though the phases of the methodology are described here sequentially, adherence to linearity is not intended (Blessing and Chakrabarti, 2009, p. 17); the phases are not performed in a strictly linear fashion in this dissertation. For example, in order to determine if the results would be generalizable (evaluation in phase 4), certain information was researched in phase 1 and studied empirically in relation to the re-design project in phase 2 (e.g. demographic information found in relation to the Canadian census data that informed a demographic questionnaire that was shared with participants). This is one example, but additional occurrences of non-linearity have occurred in the research here. DRM has been utilized as a general structure and overall flow for the dissertation research.

3.2 Qualitative methodology

To develop the dissertation research in relation to the DRM phases, this research takes a qualitative methodology orientation with mixed methods (qualitative and quantitative methods). It is important to note that the meaning of qualitative methodology is a style of research that goes beyond data type. The quantitative approach is very typical in engineering research. In Daly, McGowan and Papalambros' (2013) review of qualitative research in engineering design, they find that qualitative methods offer the opportunity to "richly illuminate processes, cultures, relationships, and motivations that impact design" (p.8). So while the qualitative approach has been used in engineering research e.g. (Chism, Douglas, and Hilson, 2010), it is not as typical as a quantitative approach and is thus explained in more detail here with particular emphasis on two of its traits – its grounding in exploration and participant perspectives.

3.2.1 The exploratory nature of qualitative methodology

One of the first significant traits of qualitative methodology is its exploratory nature. Corbin and Strauss state that, "Qualitative studies are usually exploratory and more hypothesis generating rather than testing. Therefore, it is necessary to frame the research questions in a manner that provides the investigator with sufficient flexibility and freedom to explore a topic in some depth" (2008, p. 25). A qualitative research study is thus directly related to the fundamental view of research as inquiry, as illustrated in Figure 7.

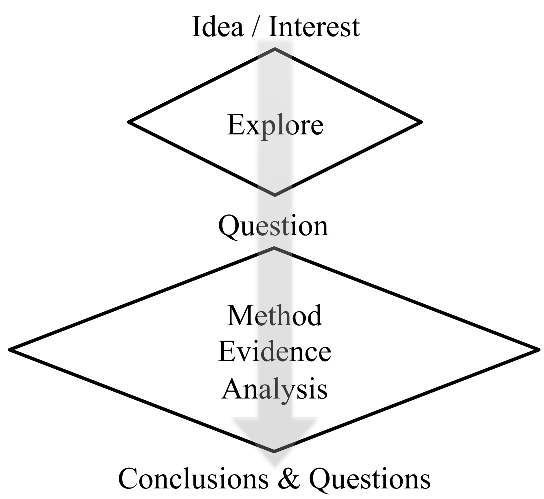


Figure 7: Inquiry methodology (after (Hudspith and Jenkins, 2001))

One of the main benefits of an inquiry (Figure 7) and qualitative approach is that it allows the researcher to explore a topic that has not been researched in depth.

This exploratory feature of qualitative methodology is particularly relevant and useful for this dissertation research. The literature review revealed the need to develop an approach for re-designing socio-technical systems that considers the critical significance of operators in collective human activity and operationalizes human value. The existing literature does not provide examples of this being performed nor does it directly study this combination of factors. It is, therefore, difficult to develop useful hypotheses in this situation, making the exploratory feature very appropriate.

To draw a hypothesis in this situation could easily lead to various problematic arguments. To base a hypothesis on the existing re-design approaches would develop an approach for socio-technical systems in the image of technical artefacts (which is what they have been intended for), which lack the 11 considerations and needs that were identified. With this tactic, it would also be difficult to clearly identify the assumptions that would be manifested from the existing approaches into the new approach. This is precisely the warning that Vermaas et al. (2011, p. 70) gave, as discussed in this dissertation's introduction. Further, to position the development of a re-design approach for socio-technical systems versus, or competing with, an existing approach for technical artefacts would also be reactionary, leading the research to be conducted at the level of the controversy between the needs and the existing approaches. An either/or approach does not serve greater understanding, only additional understanding, and an integrative approach is needed -- integrating socio-technical system theory with a re-design approach (consideration 3), inter-disciplinary acumen (consideration 2), and the system perspective (considerations 9, 10 and 11). Moreover, the dissertation research aims to regard human potential highly and develop it (consideration 11); discovering the meaning of potential requires openness for realization so that the unique challenges and opportunities in re-designing socio-technical systems can be identified. The qualitative methodology's exploration and inquiry features are well suited to an 'openness for realization.'

For these reasons, it therefore makes sense for this dissertation to research with questions and inquiry in order to develop hypotheses that can later be tested. This is why this dissertation does not list a formal thesis statement. A thesis statement is a form of hypothesis. The intent of this dissertation is to be grounded in the research problem and questions, which leads here to generating hypotheses. In other words, this dissertation research does not begin with a hypothesis (introduction) it generates them as it progresses and ultimately ends with one (conclusion).

3.2.2 The participant (emic) orientation of qualitative methodology

Another significant trait of qualitative methodology is that it is positioned to draw from the participant perspectives. In a qualitative research design, "the goal is to understand the situation under investigation primarily from the participants' and not the researcher's perspective. This is called the *emic*, or insider's, perspective, as opposed to the *etic*, or outsider's, perspective" (Hancock and Algozzine, 2011, p. 8). One of the benefits of the qualitative approach is that it allows for research to be developed and structured in relation to the participants, in order to study a situation (re-design) from the inside out, rather than from the outside in.

This participant perspective feature of qualitative methodology is particularly relevant and useful for this dissertation research. The literature review revealed that it is critical to orient an approach for re-designing socio-technical systems with human values (condition 6); respecting people as purposeful beings (condition 8); regarding human potential highly and developing it (condition 11); and operationalizing human value and potential (condition 5). The literature review also identified that in socio-technical systems, workers operate the system in collective activity to make it function and are thus inter-connected with the socio-technical system. Accordingly, socio-technical system operators are in a unique position to offer critical *in*sight on the system. By engaging socio-technical system operators as participants in this study, they have an opportunity to share their insight. The qualitative methodology develops this research directly from their participation and insight, which operationalizes humanism in the research approach and provides a vehicle for it to be manifested into the research with practice in the re-design industry project. This participant perspective feature, and exploratory nature, further align with a grounded theory approach to the qualitative methodology taken here.

3.2.3 The grounded theory approach to qualitative research

Grounded theory is a type of qualitative research that mobilizes the exploratory and emic features of qualitative methodology in generating new theory. In grounded theory the theory is derived out of the empirical evidence. In Glaser and Strauss' (1967) foundational work on grounded theory, they state that the purpose of grounded theory is to discover theory from data (p. 9) as a process (p. 32) that is "suited to its supposed uses" (p. 3). The following are some highlights of grounded theory. Grounded theory is:

- *Developed in a discussional form*: "The discussional form of formulating theory gives a feeling of 'ever-developing' to the theory, allows it to become quite rich, complex, and dense, and makes its fit and relevance easy to comprehend" (Glaser and Strauss, 1967, p. 32).
- *Supportive of the generation of substantive theories*, which are those theories developed for an empirical and pragmatic area of inquiry that may help to generate new, or reformulate previously established, grounded formal theories (Glaser and Strauss, 1967, p. 34).
- *Focused on formulating theory with conceptual categories and their conceptual properties* (aspects or elements) (p. 36), followed by hypotheses or "generalized relations among the categories and their properties" (Glaser and Strauss, 1967, p. 35).
- *Focused on formulating theory, though not necessarily distinctly from existing theories:* "Although categories can be borrowed from existing theory, provided that the data are continually studied to make certain that the categories fit, generating theory does put a premium on emergent conceptualizations" (Glaser and Strauss, 1967, p. 37).
- *Inclusive of both qualitative and quantitative data*: "In many instances, both forms of data are necessary – not quantitative used to test qualitative, but both used as supplements, as mutual verification and, most important for us, as different forms of data on the same subject, which, when compared, will each generate new theory" (Glaser and Strauss, 1967, p. 18).
- *Typically involved in 'how' and 'why' research questions* (Corbin and Strauss, 2008, p. 1).

These features and the grounded theory overall approach align with the intents and needs of the re-design study at hand as subsequently outlined.

The grounded theory overall approach that is utilized in this dissertation research follows Glaser and Strauss (1967) in the following manner. Towards the development of new grounded re-design theory, this study takes an intermediary step by building models from data in the participatory re-design of a socio-technical system. In doing so, these models of re-design practice are surfaced along with their conceptual categories in the form of inputs, outputs, constraints, and mechanisms (the investigative processes for creating them). Together, the models and their elements form a framework for the participatory re-design of a socio-technical system that supports the further development of new re-design theory with hypotheses for testing and comparison in future research (e.g. additional socio-technical system contexts for comparison). This approach is consistent with grounded theory because it works from the participatory empirical evidence gathered outwards towards theory and hypotheses. Socio-technical systems theory informs the research questions that motivate this research but it does not stipulate specific hypotheses for how the emic aspects of the re-design process should be formed; these are discovered in situ from the participant data and not prior to gathering the participant data, which is in keeping with the grounded theory approach.

The aforementioned features of the grounded theory approach are particularly useful in this dissertation. The discussional form is very appropriate to developing research with participants and with an emic perspective. The support for substantive theories in a pragmatic area relates to the dissertation's focus on developing *re-design practice in relation to participation and socio-technical systems*. The ability to create models from data and hypotheses is in line with the reasoning for why the exploratory nature of qualitative methodology aligns with this dissertation research as supported by the research questions. The relation to existing **theory** when appropriate and utilizing multiple **forms of data** aligns with the second research question. The engagement of 'how' and 'why' research questions align with the three research questions. The inter-relations between these features of grounded theory (as indicated within this paragraph by underline solid, underline dash, **bold**, and *italics*) and the research questions are correspondingly indicated below:

1. How can engaging socio-technical system operators as participants in *re-designing an assembly production system develop an approach for re-designing socio-technical systems* that operationalizes human value and potential?
2. How do **alternative (e.g. social science) and existing engineering design knowledge, practice, theory, methods, tools, techniques**, etc. mis/align with this participatory *re-design* and why?
3. What opportunities, problems, and questions arise (individual, social, and technical) in relation to the participatory *re-design of the assembly production (socio-technical) system* and why are they significant?

For these reasons, the grounded theory approach and its features align with the aims and purposes of this dissertation research and is utilized accordingly.

3.3 Research and design methods

An overview of the research and design methods, and their alignment with design research methodology and qualitative methodology, is presented in Figure 8.

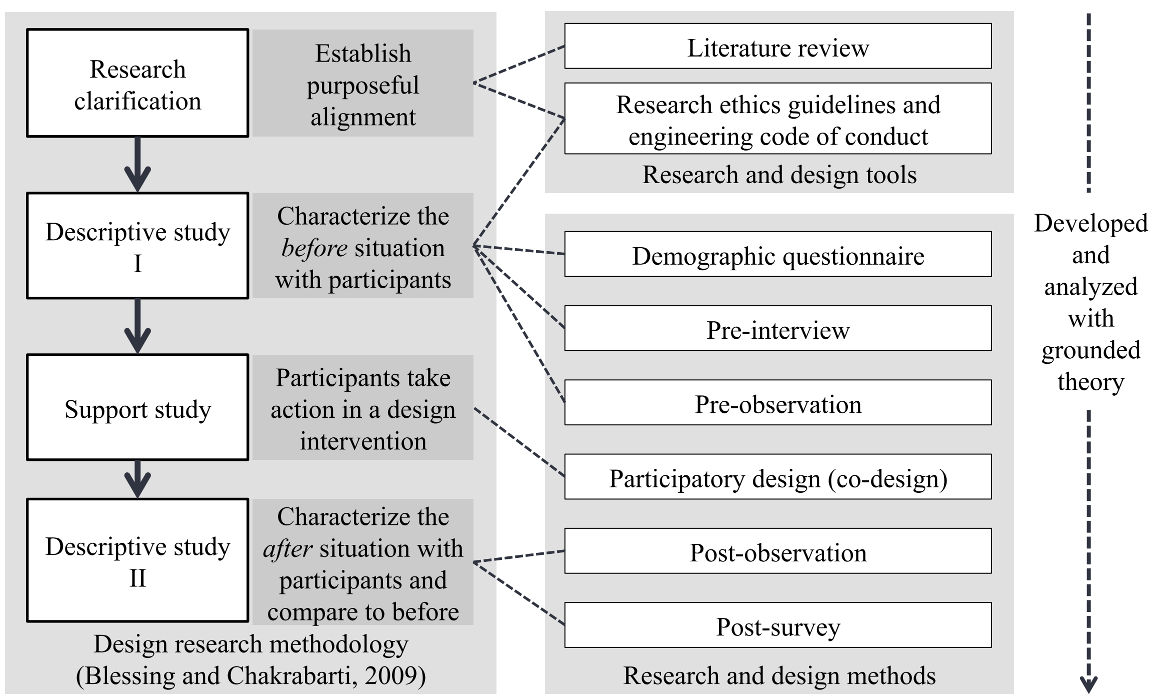


Figure 8: Overview of research and design methods utilized in the dissertation in relation to DRM and qualitative methodology

Each chapter discusses the research and design methods from Figure 8 that are relevant to that chapter. Since participatory design is a feature of this dissertation, and is rather uncommon to engineering research and practice, it is subsequently discussed in more detail.

3.3.1 Participatory design

Participatory design (PD) is a socio-technical design methodology, influenced by historical, social, and political motivations (e.g. workplace democracy). PD emerged out of Scandinavia in the 1970s out of the disciplines of computer science and information technology, and it informed what would ultimately be the study of human computer interface (HCI). It is, at heart, multi-disciplinary, because it brings together "software developers, researchers, social scientists, managers, designers, practitioners, users, cultural workers, activists and citizens who both advocate and adopt distinctively participatory approaches in the development of information and communication artefacts, systems, services and technology" (Simonsen and Robertson, 2013, p. xix).

This multi-disciplinary nature is akin to manufacturing and assembly production systems, which bring together people from diverse backgrounds (see §2.6 and §3.4) in multi- and inter-disciplinary roles for a variety of purposes (making different things in different ways for different customers). Participatory design thus aligns with the very nature of manufacturing and assembly production systems, both in terms of their function and people who fulfill their function. This dissertation research aims to align and add engineering and additional manufacturing production roles to this multi-disciplinary list of people that PD brings together (e.g. engineers, builders, lead hands, material handlers, planners, supervisors, and managers).

Participatory design may also enable the very future of manufacturing that engineers have predicted. These predictions rest on developing manufacturing systems that are changeable (Wiendahl et al., 2007) – in essence, responsive systems (Koren, 2010). In computer science and information technology, this same predicted future has led PD researchers and designers to further advocate for PD, stating that:

> *Today computer use and interaction possibilities are changing quickly with use contexts and application types radically broadening. Technology no longer consists of static tools belonging only to the workplace; it permeates work activity, homes, and everyday lives. The Scandinavian tradition of user involvement in development is facing up with the challenges of new contexts* (Sundblad, 2011, p. 176).

Thus, participatory design also supports a means towards the future of manufacturing and assembly production system re-design and operation (responsiveness to diversity).

While the fields of study that participatory design has been applied in have typically, and historically, been information technology and computer science (e.g. in the UTOPIA project of the 1980s), the definition of PD is sufficiently broad enough to be applied to engineering. Robertson and Simonsen (2013) define PD as:

> *A process of investigating, understanding, reflect upon, establishing, developing, and supporting mutual learning between multiple participants in collective 'reflection-in-action.' The participants typically undertake the two principal roles of users and designers where the designers strive to learn the realities of the users' situation while the users strive to articulate their desired aims and learn appropriate technological means to obtain them (p. 2).*

In this definition, 'users' refer to people who will interact with the information technologies being designed and 'designers' refer to people who are professionally responsible for the information technology design project (Robertson and Simonsen, 2013, p. 3). In the socio-technical system context, similarly, the 'users' refer to operators who interact with, and operate, the manufacturing and assembly production systems being designed. In engineering design, similarly, the 'designers' refer to the engineers who are professionally responsible for the manufacturing and assembly production system design.

This definition of participatory design is founded on two principles. The first principle is that PD "seeks to enable those who will use the technology to have a voice in its design, without needing to speak the language of professional technology design" (Robertson and Simonsen, 2013, p. 2). This aligns with the purposes of this research -- to respect people as purposeful beings and operationalize human value in re-designing a socio-technical (assembly production) system; and to offer participants an opportunity to engage their voices in engineering dialogue in situ via the re-design project. The second principle is that participants “who are not professional technology designers may not be able to define what they want from a design process, without knowing what is possible. A process of mutual learning for both designers and users can inform all participants’ capacities to envisage future technologies and the practices in which they can be embedded” (Robertson and Simonsen, 2013, p. 2). This seems especially relevant in the re-design of manufacturing and assembly production systems, as engineering knowledge is often perceived as specialized knowledge.

These principles are operationalized through the participatory design methods within the broader participatory design methodology. Muller and Kuhn (1993) provide a summary of typical participatory design methods, which is visualized earlier in Figure 2 (§2.5) and is summarized in the following Table 9.

		Position of the activity in the development cycle		
		Early		Late
Who participates with whom in what	Users directly participate in design activities	Co-design or co-development; Mock-ups	Prototyping (low-tech)	Participatory ergonomics; Theatre for design
		Card games; Semi-structured conferences	Prototyping (video, storyboard, cooperative, & collaborative)	Cooperative evaluation
	Designers participate in users worlds	Future solutions; Ethnographic methods; Contextual inquiry		Participatory analysis of usability data

Table 9: Summary of Muller and Kuhn's (1993) participatory design method comparison

The specific method of participatory design utilized in this research is co-design, which is positioned early in the design cycle and with participants directly taking action in design activities (highlighted in Table 9).

The participatory design methods develop mutual learning “that reveals goals, defines problems, and indicates solutions, with the aim of designing sustainable uses of IT based on a specific problem within the company” (Bødker, Kensing, and Simonsen, 2004, p. 13). The intent is very pragmatic and immediate to the participants and industrial research context. The re-design problem from the company perspective in the industrial re-design project being studied in this dissertation is the following:

> *At [Company], custom assemblies are designed and manually assembled per the voice of our customers. Since 2003, orders have grown by an average of 25.5% year-to-year. In 2003, 16,373 assemblies were designed and assembled. In contrast, 103,450 assemblies were designed and assembled in 2012. While this growth has created substantial business and employment opportunities, challenges now exist in process versatility (396 unique assembly configurations and products), attaining and maintaining quality standards, and high turnover of temporary employees. In turn, this has created a need to redesign the assembly process. (Excerpt, company letter)*

The re-design problem is further explored from the participant perspective in several chapters of this dissertation, and it is positioned in relation to the dissertation research problem as outlined in §1.1 and §2.7.

In this dissertation, participatory design and its action research orientation engages socio-technical system operators as participants in re-design as transformation, creating change in their assembly production system. This offers an immediate research meaning for the participants, which they can view through their own eyes and through their participation in the transformation. An examination of this transformation and action is utilized to develop grounded theory models. This research accordingly moves from the particular to the general, from data to models, to relate the immediate experience of re-designing an assembly production system to the broader situation of re-designing a socio-technical system. The immediate situation and context is important as a unit of analysis within which the findings are developed and discovered, which helps to understand its transferability to other situations and contexts.

3.4 Industrial context and participants

The assembly production system studied in this research is described here with technical, social, and individual contexts. The assembly production system is an assemble-to-order system. After a customer order is received, batch production is performed according to the order (maximum volume of 200 final assemblies observed). This means that production is intermittent. The final assemblies consist of 5 main component types (a, b, c, d, and e) that have numerous sub-types (outlined in Table 10);

component b is the platform with five-subtypes observed. These components are assembled with the relationships outlined in the precedence diagram in Table 10.

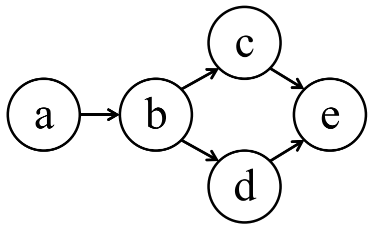
Precedence graph of the component order of assembly	Assembly variant combination descriptions	Component type				
		a	b	c	d	e
	# of sub-types	4	5	37	4	1
	Min # different sub-types	0	1	1	0	1
	Max # different sub-types	1	1	8	1	1
	Min # of components	0	1	24	0	2
	Max # of components	1	1	60	2	15
	Flexible (F) or rigid (R)	F	F	R	F	F

Table 10: Final assembly component variants and precedence (from the pre- and post-observation)

The components in Table 10 are manually assembled by two builders. This position is assigned on a shift basis, with temporary, part-time, or full-time employees. The builders perform this process with a fixed product layout, as illustrated in Figure 9. In Figure 9, the letters ‘a’ to ‘e’ represent the components per Table 10 with their sub-types indicated by the letter followed by a number (e.g. c5); ‘G’ represents a garbage can; ‘WO’ represents a work order; ‘L’ represents a label; and ‘T’ represents a tape gun.

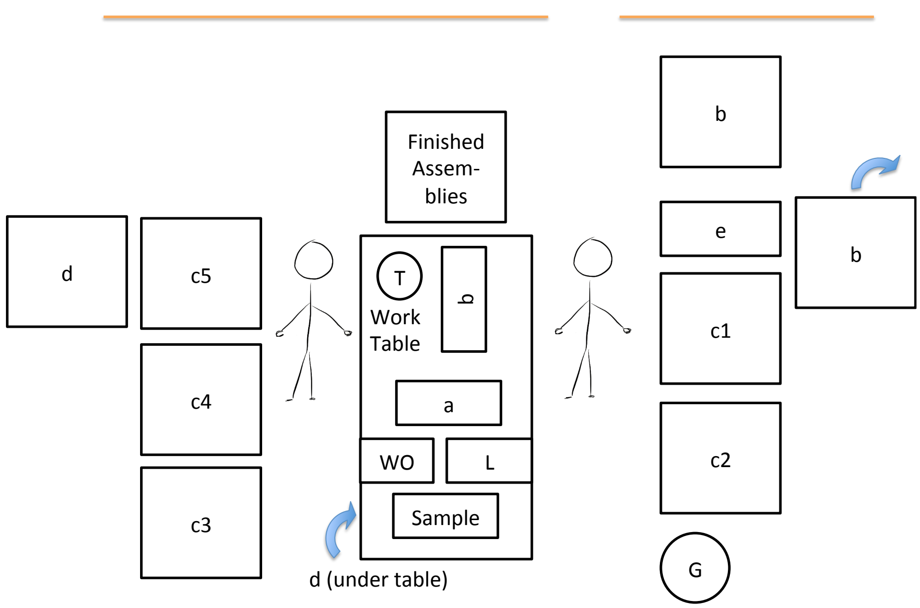


Figure 9: Fixed product layout (from the pre-observation)

In addition to the work that is performed by the builders in relation to Figure 9, the broader assembly production system includes socio-technical system operators working in several other roles (cf. Figure 10).

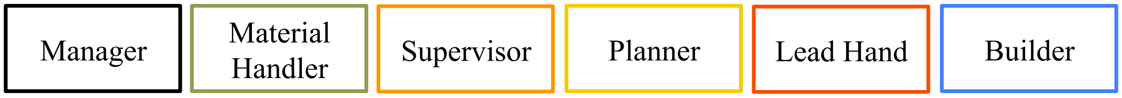


Figure 10: Socio-technical system operator roles

Of the roles in Figure 10, the 32 participants in this study represent the roles of manager, supervisor, planner, lead hand, and builder. These roles contribute to multiple perspectives, which is emphasized in qualitative methodology: “In a qualitative study, it is important to obtain as many perspectives on a topic as possible” (Corbin and Strauss, 2008, p. 26). The socio-technical system operators, in relation to their roles in Figure 10, perform various activities within the assembly production system as illustrated in the process map in Figure 11. Figure 11 is an aggregate of the participant responses to the pre-interview questions: How would you describe the current assembly process? How would you describe your work with the current assembly process?

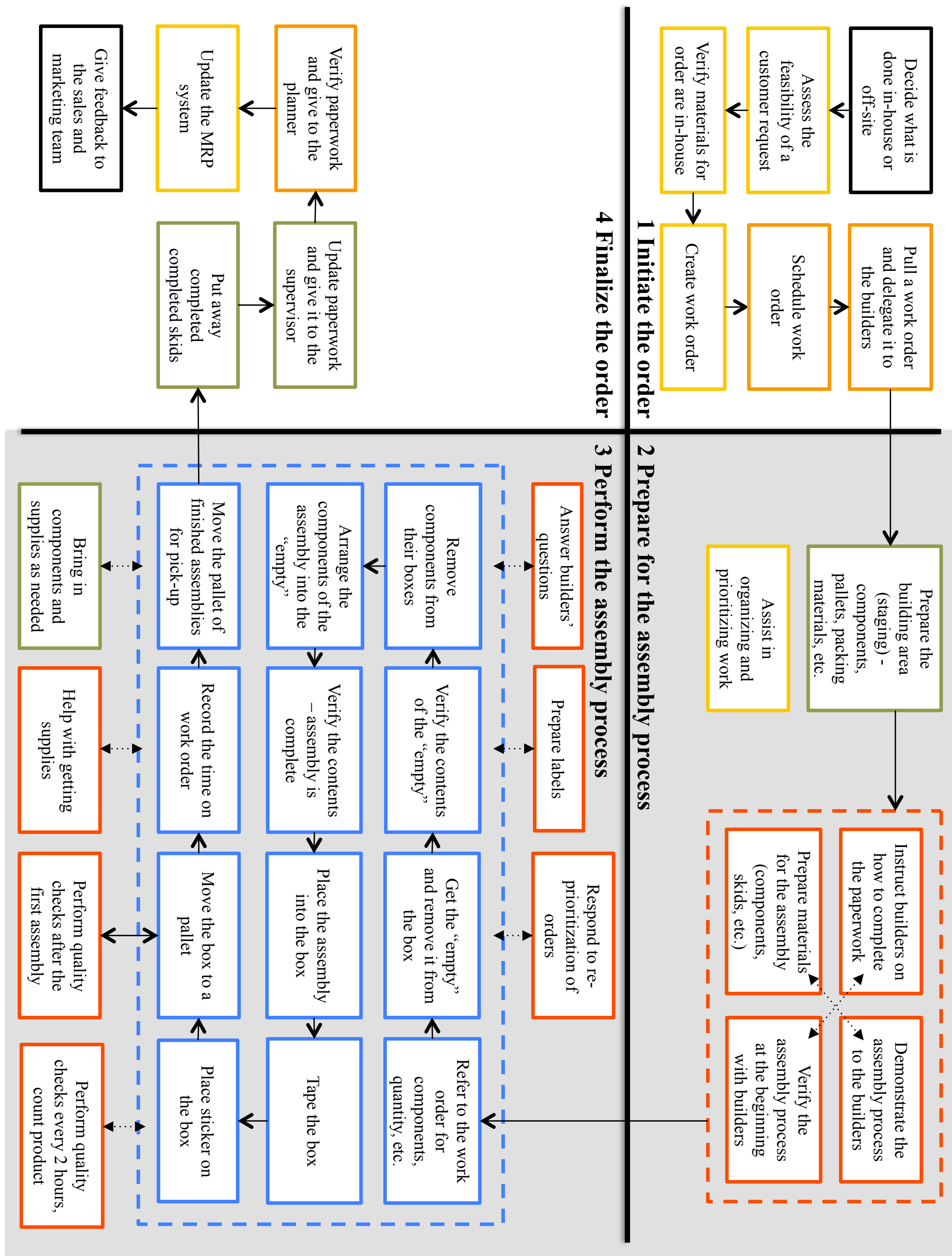


Figure 11: The initial assembly process and work (from the pre-interview, n=8)

Figure 11 shows the four critical quadrants, or phases of the assembly process, grouped from the participant pre-interview responses. The highlighted quadrants/phases 2 and 3 are considered in scope for the re-design project. They also highlight that the focus of this research is on assembly production and not Design for Assembly (DFA) rules.

The work in Figure 11 is performed in relation to the social context of the industrial setting. It is a unionized environment where no prior participatory design events had taken place. In particular, it is important to regard the participant perspectives on experimenting in the organizational culture, since re-design involves trying new ideas and transformation. Inquiring into experimenting is also a way to ask about the organizational culture's approach to change without it being a leading question and to inquire directly into experience. Figure 12 is an aggregate of the participant responses to the pre-interview statement: "At the [facility] experimenting is..."

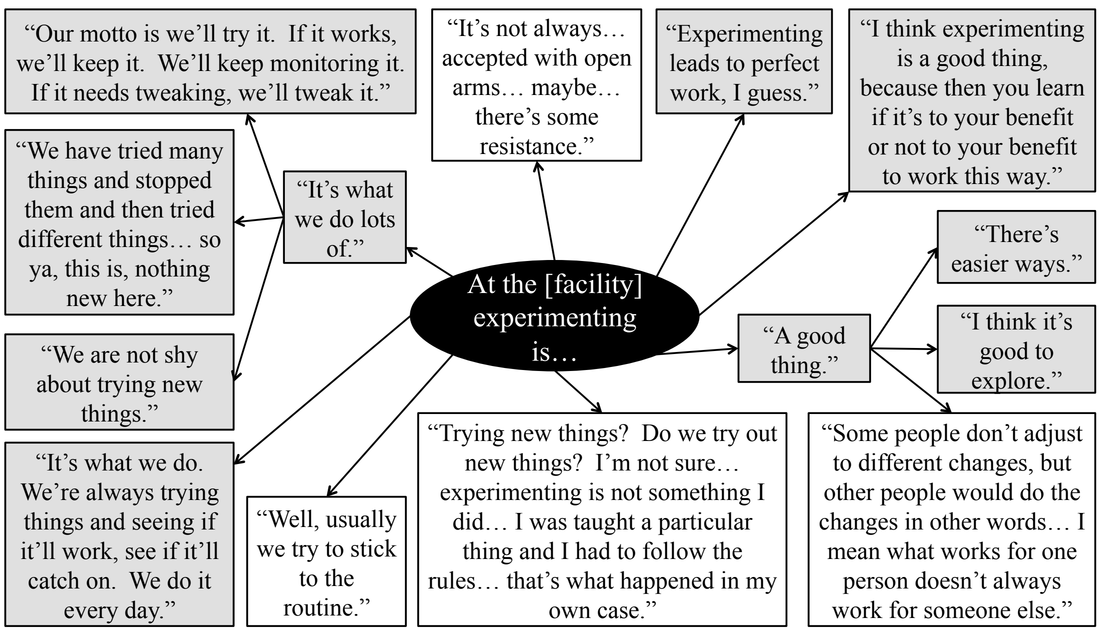


Figure 12: Pre-interview participant quotes on pre-disposition to experimenting (n=8)

The quotes in Figure 12 span the roles of manager, supervisor, planner, lead hand, and builder. These responses identify that there is some hesitancy and skepticism towards experimenting (boxes in white) along with a significant degree of openness to experimenting (boxes shaded in grey) in the organizational culture.

The participants themselves can also be understood through a range of demographics (from the demographic questionnaire, n=27), including age (Figure 13), sex (Figure 14), visible minority status (Figure 15), and education (Figure 16). These demographics explain the industrial context with the broader Canadian manufacturing context using the North American Industry Classification Systems (NAICS) code 31-33 for manufacturing. It is also noted here that the demographic trends can change within the different manufacturing sub-codes (specific manufacturing industries) but the specific industry cannot be named here due to confidentiality.

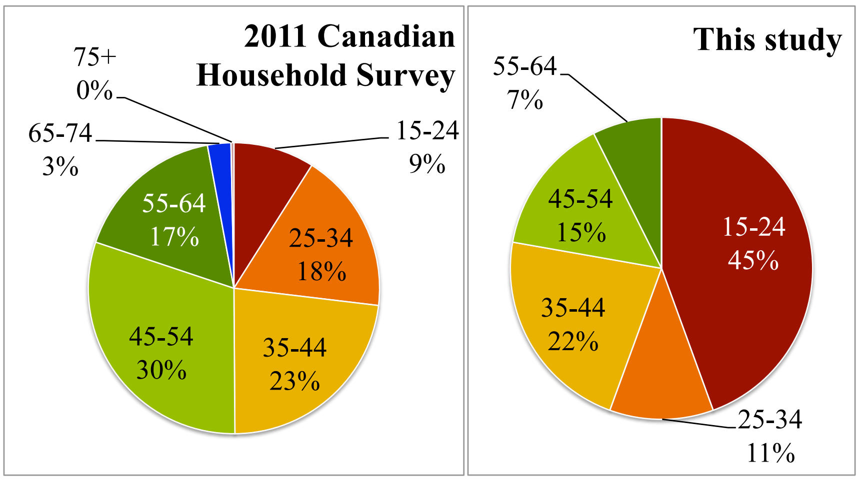


Figure 13: Age demographics of the 2011 Canadian Household Survey and research study participants (n=27, questionnaire)

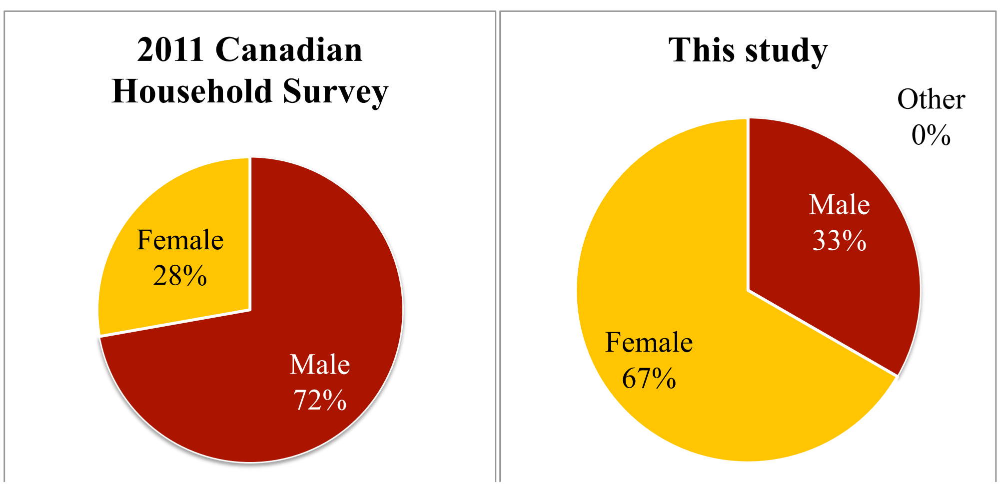


Figure 14: Sex demographics of the 2011 Canadian Household Survey and research study participants (n=27, questionnaire)

In Figure 15 it should be noted that "visible minority" is defined in the Canadian census and household survey, and identified on the demographic questionnaire, with the following categories: Chinese, South Asian, Filipino, Latin American, Southeast Asian, Arab, West Asian, Korean, Japanese, another visible minority that is not previously stated, or multiple visible minorities.

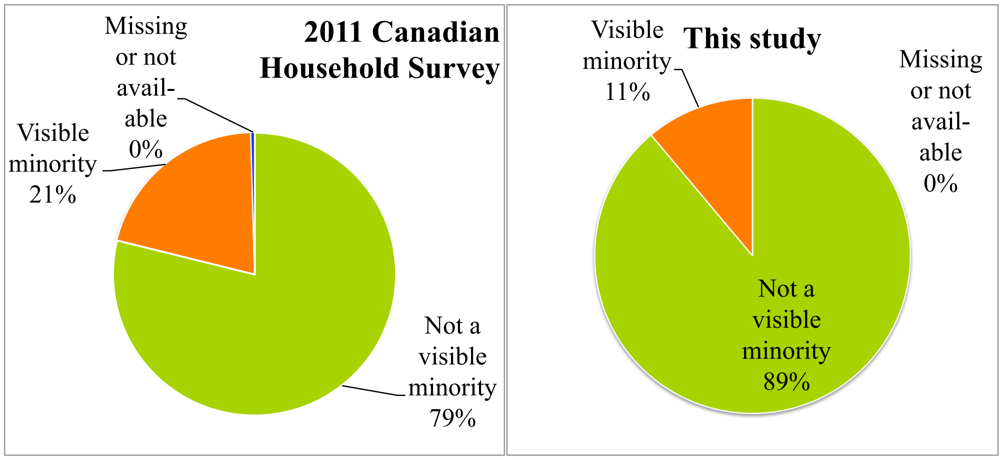


Figure 15: Visible minority demographics in the 2011 Canadian Household Survey and research study participants (n=27, questionnaire)

In the educational data collected (Figure 16), some participants noted their majors. College, CEGEP, or non-University certificate or diploma majors reported were: child and youth, business management, and business accounting. University certificate or diploma below the bachelors level majors reported were: history and biology. University bachelor's degree majors reported were: psychology, sociology, electric and computer engineering, english, criminology, geography, mechanical engineering, economics, and visual arts. University graduate degree (Masters, PhD, or professional schooling) majors reported were: art therapy graduate studies. Other (please describe) education and majors reported were: military education. These majors highlight the multi-disciplinary educational background of the participants, further described in Figure 16.

For the educational data shown in Figure 16, the demographic questionnaire participants were asked for what education "applies to you" versus the "highest completed" as stated in the Canadian Census and Household Survey. This does not enable a direct comparison, but it was asked in this way intentionally. (1) It was asked to capture important information such as partial completion of education. Several of the participants are current students and this is important information to capture to accurately portray the context. (2) The "highest completed" education asserts a hierarchy that is intentionally not projected onto this research. E.g. who is to say that an apprenticeship certificate is higher or lower than a college diploma or bachelors degree? Is a military education higher or lower than these? Etc. PD is grounded in democratic empowerment across socio-technical operator roles (Figure 10), so reinforcing societal education hierarchy or establishing one within the context would confuse the intent of the research. Participants were asked what education “applies to you” to enable open self-description, resulting in a +100% cumulative total because people self-described themselves relative to multiple categories.

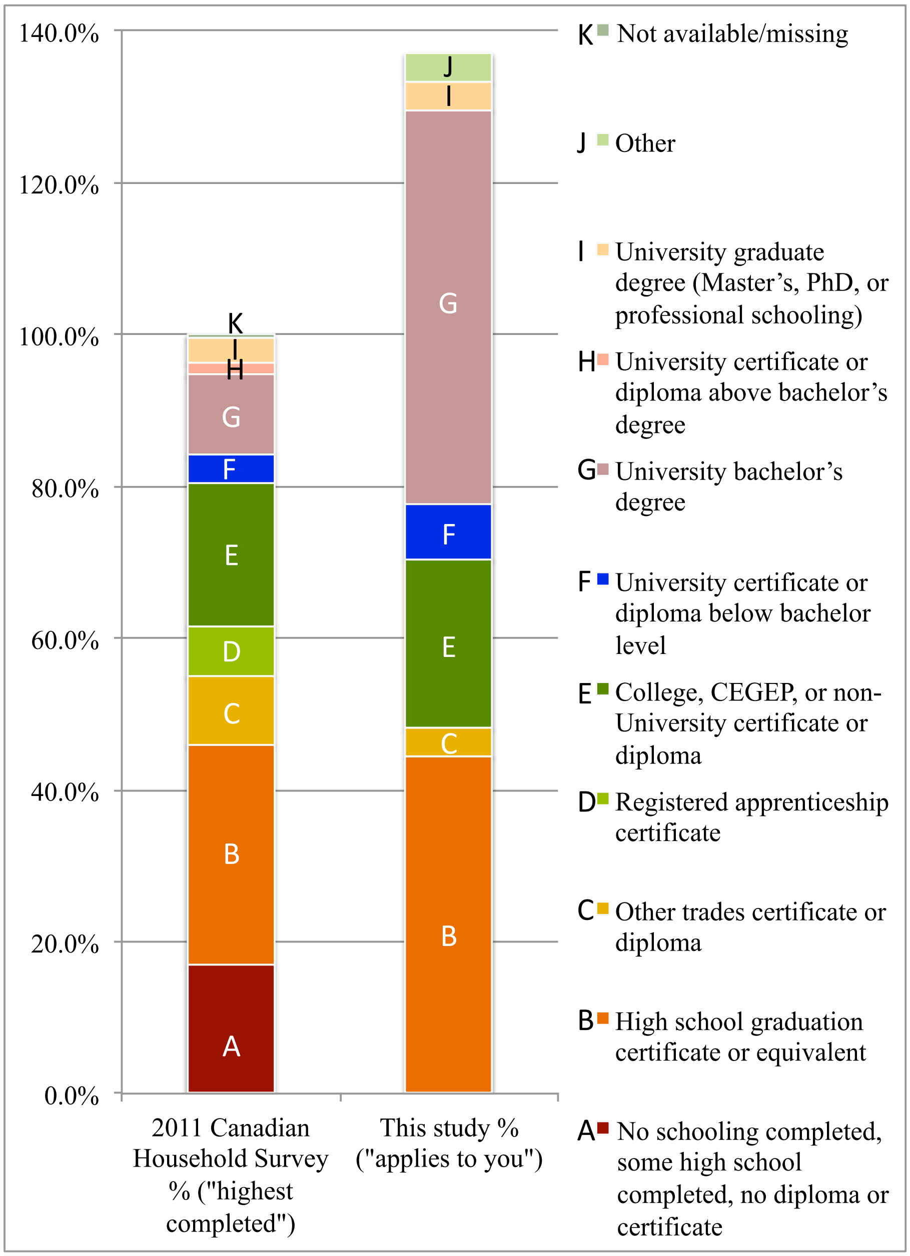


Figure 16: Education demographics of the 2011 Canadian Household Survey and research study participants (n=27, questionnaire)

These context perspectives are described with data from the pre-interview, pre-observation, and questionnaire. This means that the understanding of this context is derived from the socio-technical operator participation. The research development is accordingly informed from the participant perspective from the onset, which is in keeping with an emic qualitative approach.

3.5 Overview of the dissertation research design

An overview of the research and design methods in this dissertation, their sequence, associated analytical methods, techniques, tools, etc. is shown with an IDEF0 model. The IDEF0 model format used here is outlined in Figure 17.

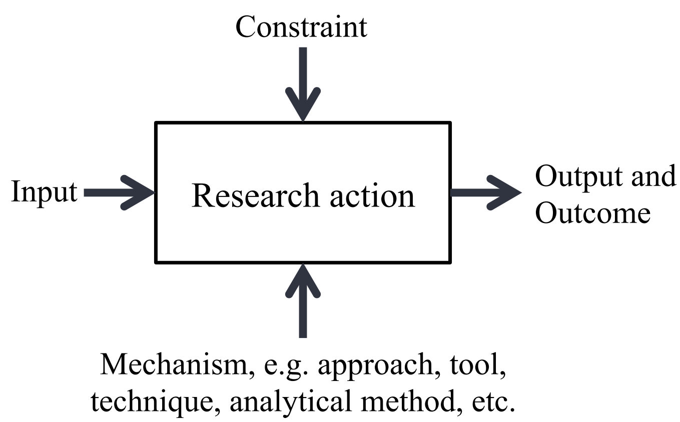


Figure 17: IDEF0 model format

The research design IDEF0 models are organized into six pages, from Figure 18 to Figure 23. The research actions are organized and numbered into a linear, sequential flow. This helps to orient the reader of this dissertation to the logic and format in which the research here is presented and was generally conducted. It is significant to note, however, that this flow evolved in various iterations and at times was non-linear in development (e.g. certainly in the planning stages, several feedback loops back to analysis, iterative analysis, etc.). The IDEF0 representation, therefore, is an organizational structure that provides an overview of the dissertation research in hindsight as opposed to a strict account of its forward development.

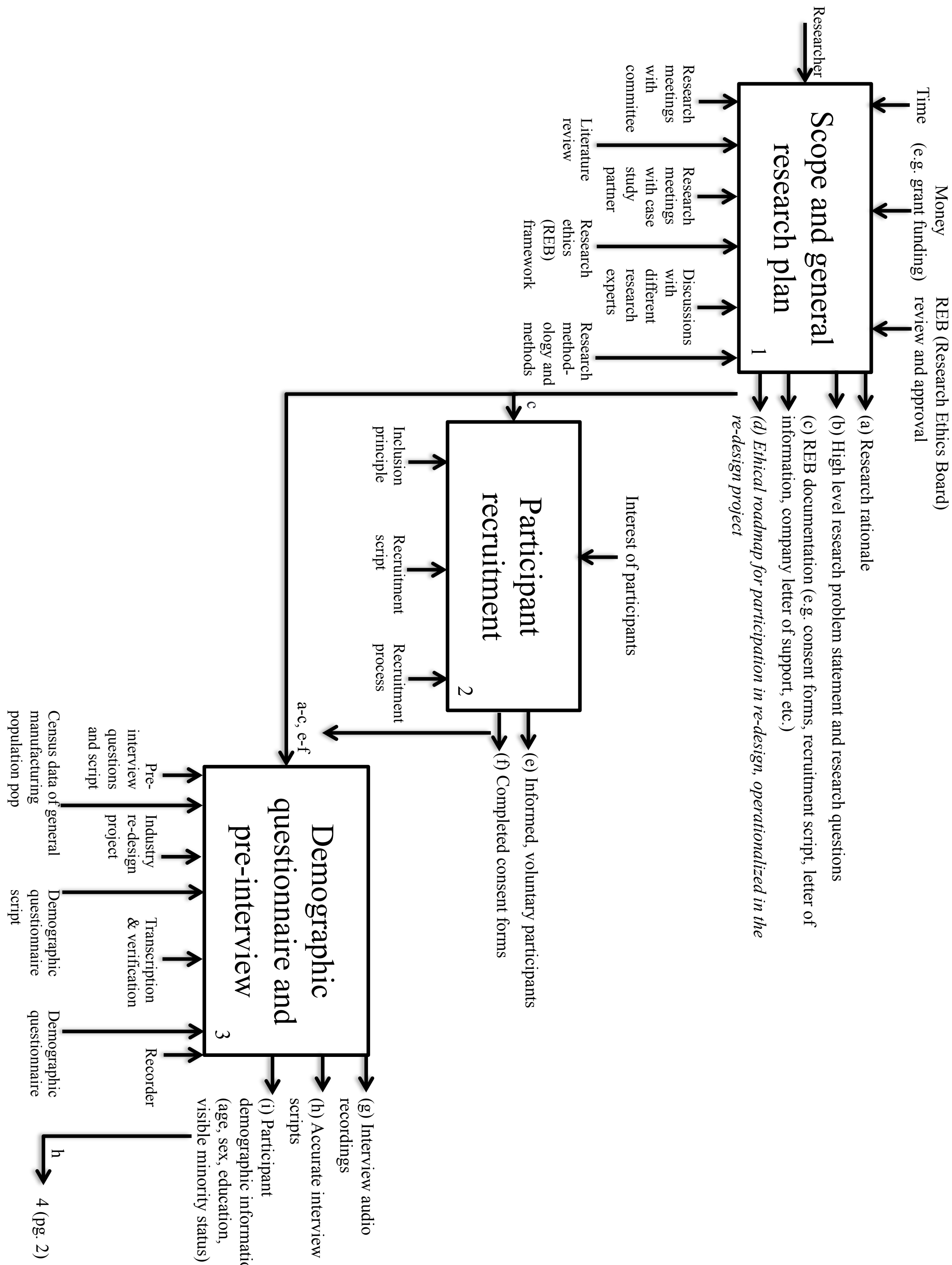


Figure 18: IDEF0 of research design (page 1)

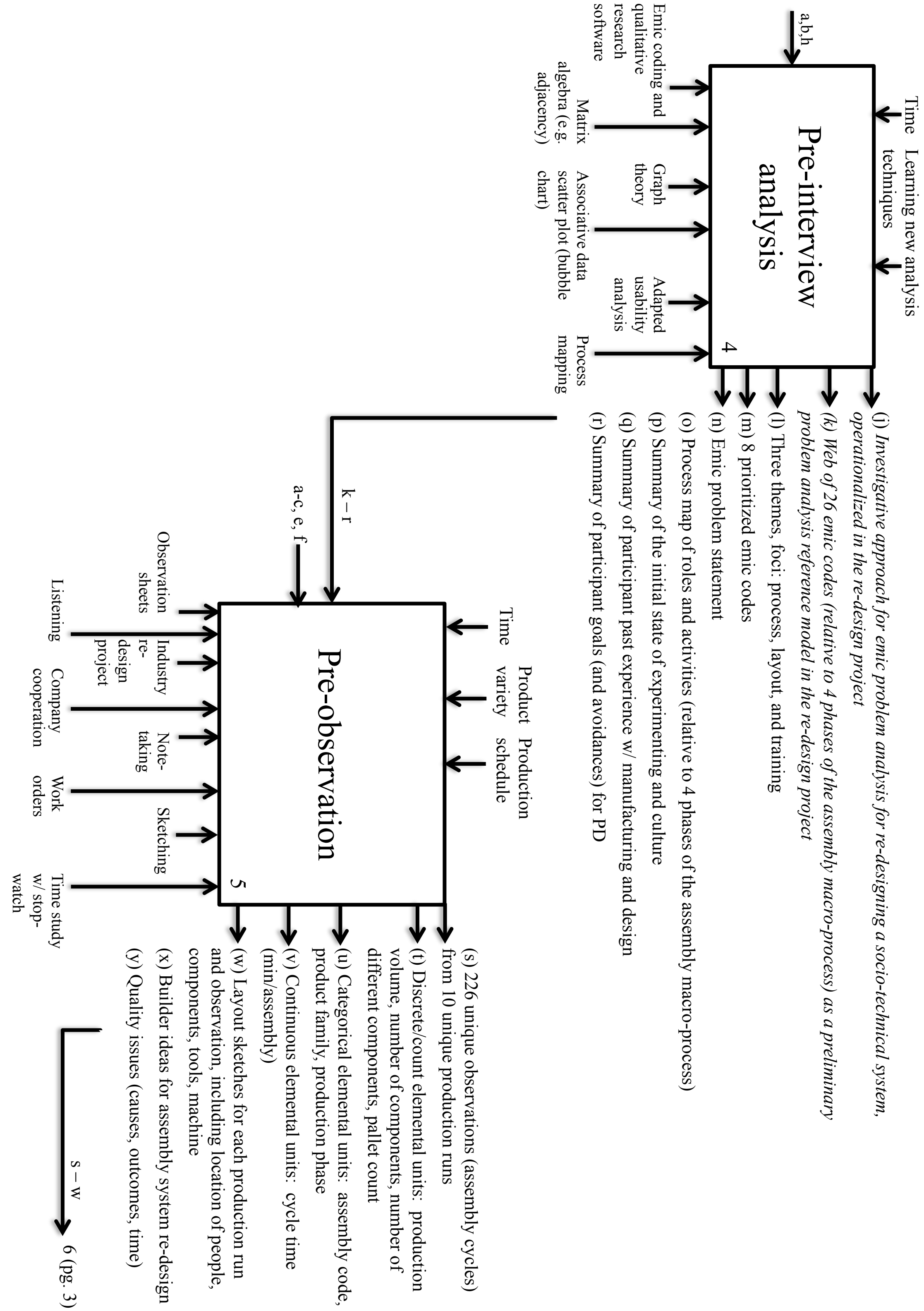


Figure 19: IDEF0 of research design (page 2)

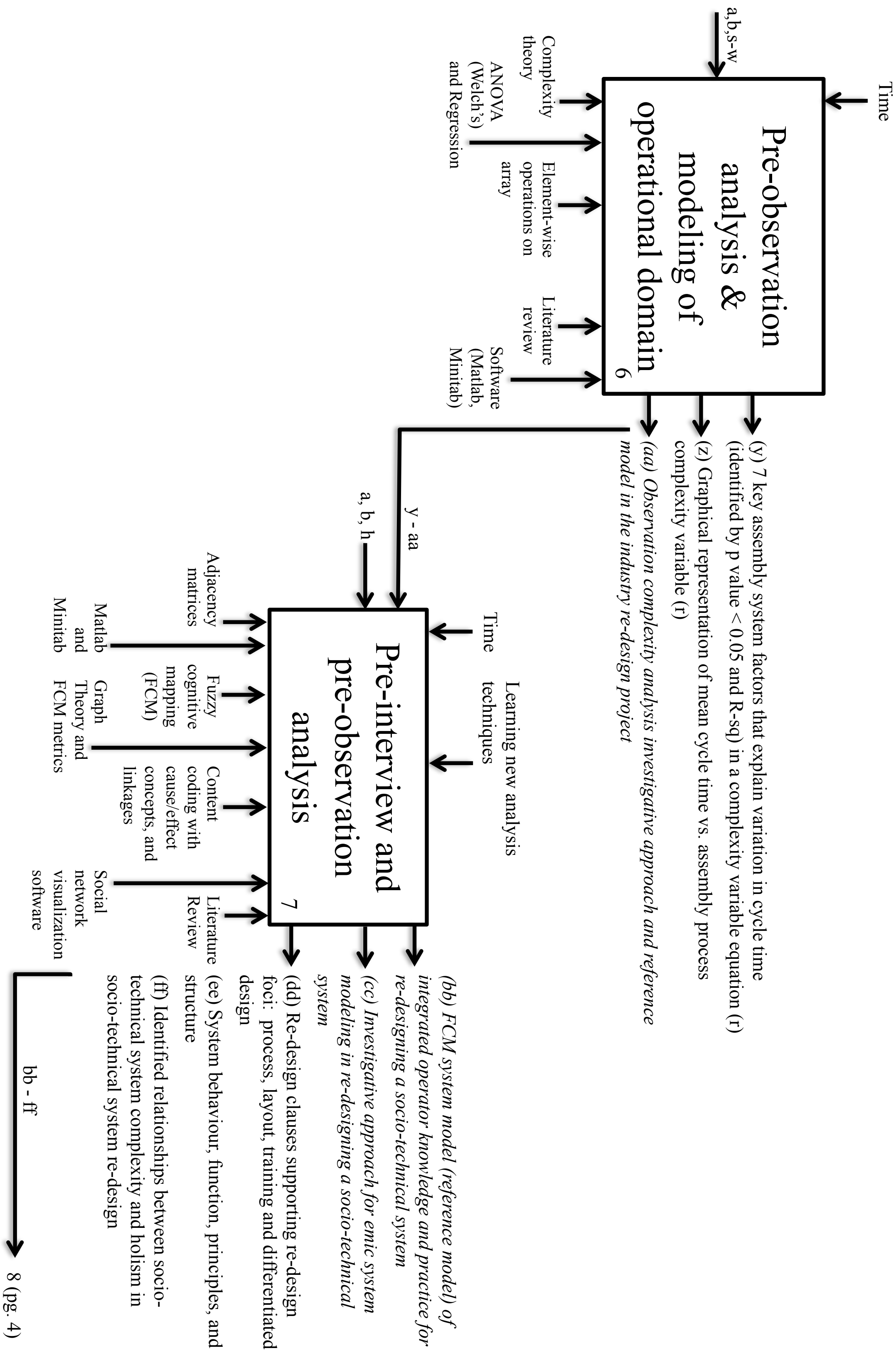


Figure 20: IDEF0 of research design (page 3)

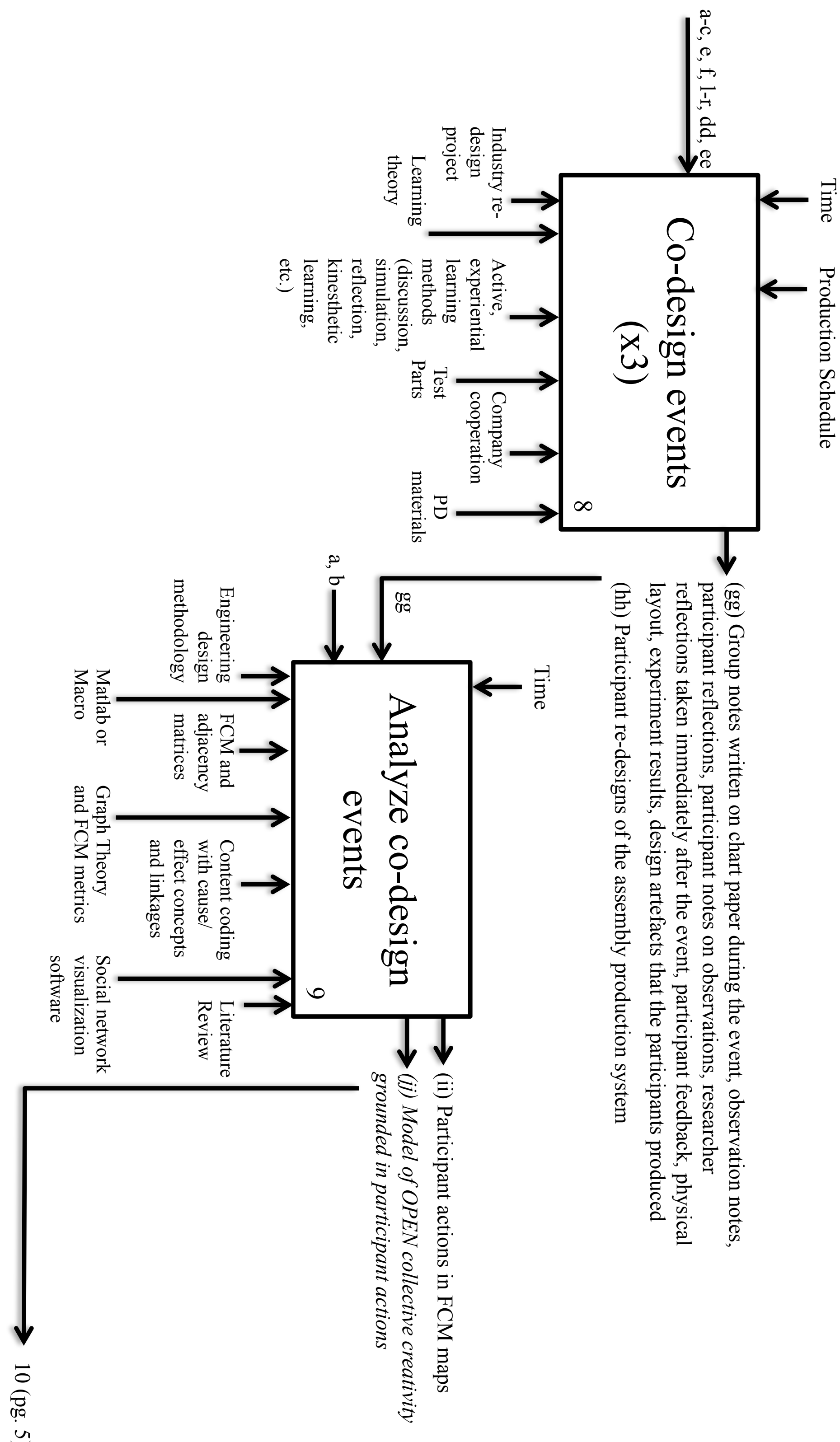


Figure 21: IDEF0 of research design (page 4)

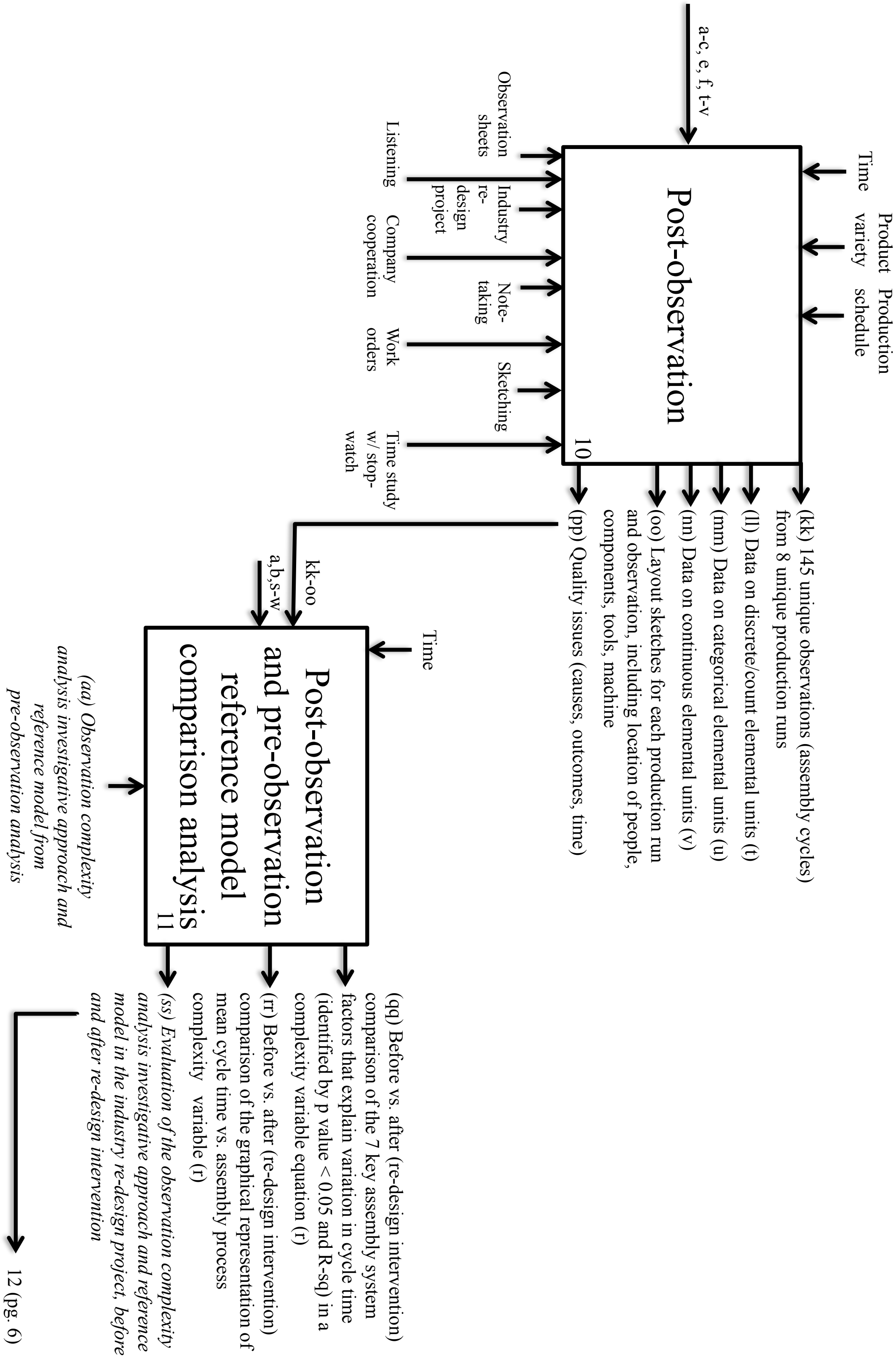


Figure 22: IDEF0 of research design (page 5)

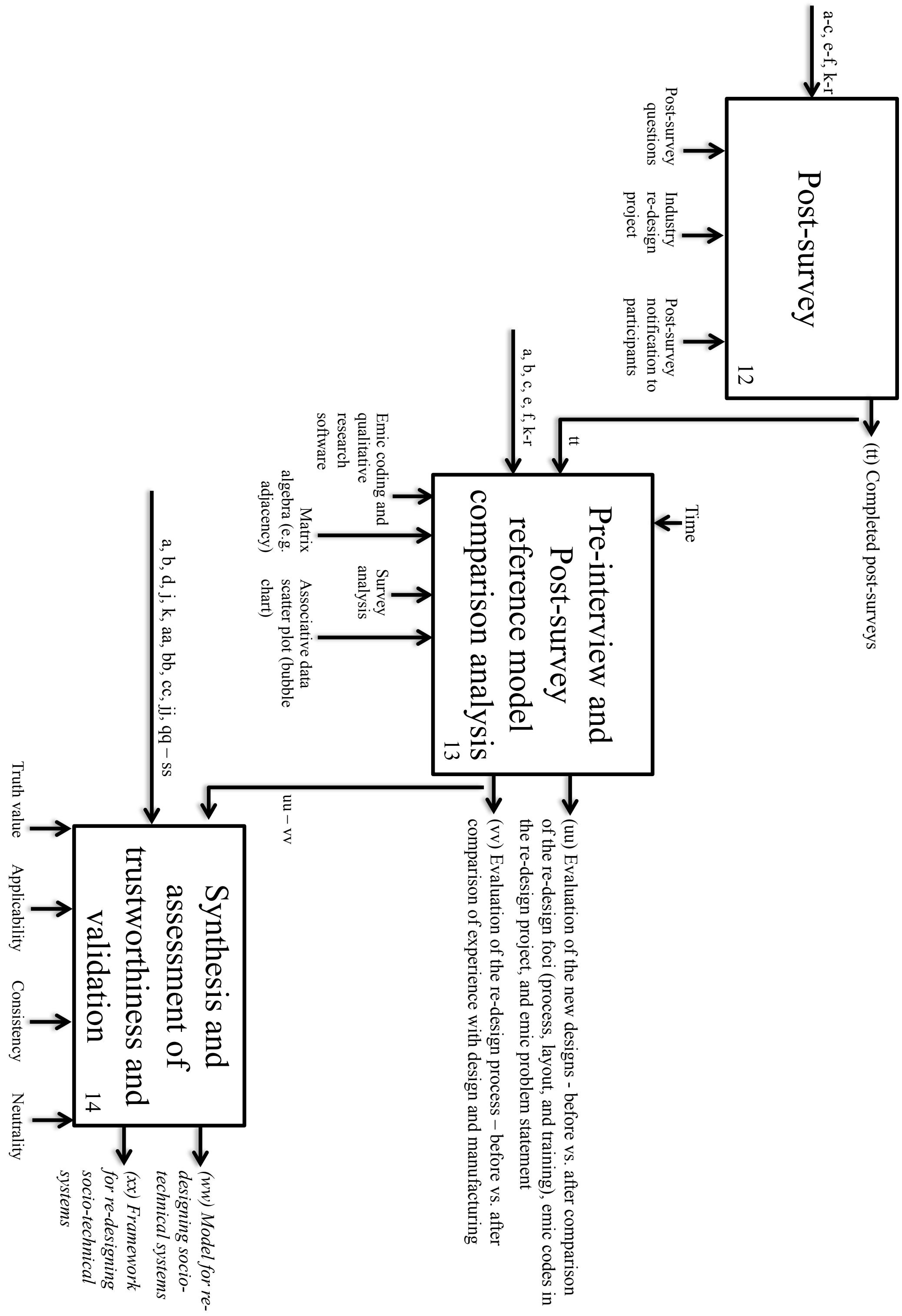


Figure 23: IDEF0 of research design (page 6)

The research actions from Figure 18 to Figure 23 -- and their inputs, outputs, outcomes, constraints, and mechanisms -- are described in the subsequent chapters per Table 11. The research action number in Table 11 refers to the number in the bottom right corner of each research action rectangle in Figure 18 to Figure 23.

Chapter	Focus (contribution to the STS re-design framework)	Related research actions (in Figure 18 to Figure 23)
Chapter 4	Ethical considerations for participation	1 Scope and general research plan 2 Participant recruitment
Chapter 5	Emic problem analysis	3 Demographic questionnaire and pre-interview 4 Pre-interview analysis
Chapter 6	Emic system modeling	5 Pre-observation 6 Pre-observation analysis and modeling of the operational domain 7 Pre-interview and pre-observation analysis
Chapter 7	Collective creativity	8 Co-design events 9 Co-design event analysis
Chapter 8	Differentiated designs	8, 9
Chapter 9	Emic system model evaluation (pre- and post-observation comparison)	5, 6 10 Post-observation 11 Post-observation and pre-observation reference model comparison analysis
Chapter 10	Emic problem evaluation (pre-interview and post-survey comparison)	3, 4 12 Post-survey 13 Pre-interview and post-survey reference model comparison analysis
Chapter 11	Discussion	1-13 14 Synthesis and assessment of trustworthiness and validation
Chapter 12	Conclusion	1-14

Table 11: Research actions and foci of Chapters 4 to 12

The introduction and conclusion of each chapter in Table 11 is organized as follows.

Each chapter begins by outlining the focus of the chapter as a step in the participatory approach for socio-technical system re-design developed in this dissertation. Next, the motivation for this focus is outlined with the literature and specific research question(s). The chapter research question(s) are related back to the dissertation's research methodology, corresponding to the principles of qualitative methodology and to a position in the design research methodology process (Figure 6). An overview of the specific research and design methods, and analytical techniques, are provided as the chapter's investigative approach. The introduction finishes with statements on the use of any copyright material within the chapter (if any).

Each chapter concludes by summarizing the chapter as a step in the dissertation's model for re-designing a socio-technical system. This step is summarized with an IDEF0 model, per the format in Figure 17. This format summarizes the key contributions of each chapter to this dissertation's research question 2 (inputs and mechanisms) and research question 3 (constraints, outputs, and outcomes). These contributions collectively summarize the chapter as a step in the developed approach for socio-technical system re-design, contributing to research question 1 (the model of socio-technical system re-design). The chapter concludes with highlighting the chapter as a step in the dissertation's model (Figure 24) and framework for re-designing a STS.

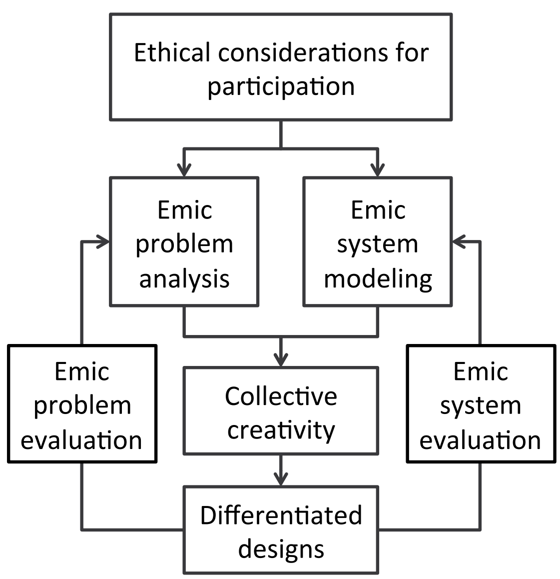


Figure 24: The developed model for re-designing a socio-technical system

4 A roadmap of ethical considerations for participation in socio-technical system re-design

The first step in developing a participatory approach for socio-technical system re-design is to understand what participation means. In the participatory design (PD) literature, genuine participation is defined as “the fundamental transcendence of the users from being merely informants to being legitimate and acknowledged participants in the design process… inviting users to such collective discussions and reflections requires a trustful and confiding relationship between all participants” (Robertson and Simonsen, 2013, p. 5). Participatory design requires a trusting and confiding relationship between all participants *and* with all facilitators, such as researchers and engineers in the re-design study and framework at hand.

This dynamic is well explored in research ethics, where researchers establish trust and confidence between participants and researchers by employing the principles of respect for persons, concern for welfare (or beneficence/non-maleficence), and justice. These ethical principles are articulated in Canada’s *Tri-Council Policy Statement (2): Ethical Conduct for Research Involving Humans (2010)* and derive from the *Belmont Report* (National Commission for the Protection of Human…, 1979). Additionally, Canada’s *Tri-Council Policy Statement* defines a research participant as “an individual whose data, or responses to interventions, stimuli, or questions by a researcher are relevant to answering a research question” (Government of Canada, 2010, p. Glossary). Consequently, for the purposes of this dissertation research, the term ‘participant’ has dual meanings – a participant in research and a participant in participatory design.

The ethical considerations regarding participation are critical to research *and* practice. Ethics is integral to participatory design: “Participatory design, then, has at its core an ethical motivation to support and enhance how people can engage with others in shaping their world including their workplaces, over time. The ethical motivation is not some optional extra to accessorise any understandings and specific practices of participatory design. It is its essence and structures its definition and ongoing development” (Robertson and Wagner, 2013, p. 65). The ethical considerations for PD in engineering have not been found to be documented in the literature. In turn, defining a framework for the participatory re-design of a STS requires, first, a clear understanding of the ethical considerations for participation in research and practice.

In turn, the research in this chapter asks: What are the ethical considerations involved in the participatory (re-)design of a socio-technical system, in engineering research and practice? How can they be operationalized in an industrial re-design project? These questions ground the research in the qualitative methodology approach (§3.2) and develop the criteria and descriptive study I of design research methodology (§3.1, Figure 6). The intention here is to explore this chapter's research question *in situ* in the re-design of an assembly production system and socio-technical system archetype. The industrial context and participants are described in detail in §3.4. The purpose is not to provide a universal solution; rather, the intent is to plot the ethical considerations in relation to the context and project at hand as an ethical roadmap. With this roadmap, engineering researchers and practitioners can navigate and further shape the roadmap's landscape and routes in additional participatory re-design projects and socio-technical system contexts.

This chapter sets out to develop a roadmap of ethical considerations for participation in socio-technical system re-design by relating three perspectives. (1) Research ethics and its three principles are defined (§4.1) and then related to the industrial re-design project to provide examples of their operationalization in the study context (§4.2). This grounds the developed roadmap in *participatory* ethical considerations. (2) Principles from a professional engineering code of ethics are related (§4.3), integrating professional engineering ethics with the developed roadmap and highlighting emphases distinct to participation. (3) Finally, ethical questions from the participatory design literature are aligned with the roadmap (§4.4), highlighting how the developed roadmap provides specificity to these broader questions.

In this chapter, the primary ideas and sections §4.1 to §4.4 (including tables and figures) are taken from the paper, "An Ethical Roadmap for Engineering Participatory Design and Socio-Technical Participation" (Townsend, Boulos, and Urbanic, 2014). The titles of the sections, tables, and figures have been changed to align with this dissertation; any wording additions are indicated with square brackets. This conforms to the ASME copyright agreement, which states “Authors may… display all or part of the Paper, and create derivative works in print or electronic format” (AMSE copyright agreement, Appendix N).

4.1 Research ethics

For the purpose of this study, the Canadian Tri-Council Policy Statement on research ethics is utilized, which focuses on three internally accepted core-principles of research ethics: respect for persons, concern for welfare, and justice (Government of Canada, 2010).

The first research ethics principle, respect for persons, can be understood directly or indirectly (e.g. through data). This principle recognizes the autonomy of individuals who have the ability to make informed and voluntary decisions. This decision must be made on an ongoing basis and based on clear information about foreseeable risks and benefits (informed) and it must not be coerced or influence (free and voluntary).

The second research ethics principle, concern for welfare, can be understood in terms of understanding and weighing risks and benefits. Risk can be related to probability (the likelihood that a participant will suffer any harm) and magnitude (the severity of harm). Common categories of risk are: physical; psychological e.g. feelings of betrayal from deception; economic e.g. job security; and social harm e.g. altering a person’s standing in a social group. Other aspects of risk that need to be considered include assessing vulnerability (e.g. psychological) and the protection of the participant’s data (e.g. identifiability, storage, destruction, and use). The benefits can be regarded as direct (e.g. at the time of involvement) or indirect (e.g. advancement of knowledge in a discipline, benefits to the community, or benefits to society generally). In a proportionate approach, the participant is not exposed to unnecessary or unavoidable risks and the potential benefits outweigh the foreseeable risks. It is worth nothing that in engineering practice, cost/benefit analyses are used analogously to risk/benefits analysis outlined here.

The third research ethics principle, justice, can be understood in terms of aiming to treat people fairly and equitably. Fairness involves treating all people with equal respect and concern for their welfare, which is not necessarily treating everyone the same. Equity involves the distribution of the benefits and burdens of research participants. In doing so, the researcher also recognizes his/her responsibility in being aware of vulnerable circumstances in the research study, not to create such circumstances, to avoid misunderstandings, and to be aware of the context. The inclusion and exclusion of participants is justified by the research questions, research goals, and available participant population.

The research ethics framework begins by defining the research rationale (including a literature review), research questions, research methods, and test instruments. The principles of research ethics are then operationalized (Figure 25).

		Research Ethics Principles		
		Respect for persons	Concern for welfare	Justice
Operationalized Through…	Capacity for consent	✔		
	Informed consent process	✔		
	Ongoing consent process	✔		
	Compensation or incentive	✔		
	Participant withdrawal process and data implications	✔		
	Recruitment script	✔		✔
	Letter of information	✔		✔
	Consent form	✔		✔
	Feedback, debriefing of results			✔
	Formal recruitment process			✔
	Participant inclusion and exclusion principle			✔
	Permission and letter of support from company	✔	✔	✔
	Possible risks (type, magnitude, probability) per method		✔	
	Group vulnerability (type, magnitude, probability) per method		✔	
	Risk matrix (vulnerability vs. risk)		✔	
	Management or minimization of risks		✔	
	Benefits (direct and indirect)		✔	
	Confidentiality/anonymity (e.g. degree of identifiability)		✔	
	Storage and disposal of records		✔	
	Data access		✔	

Figure 25: Matrix of research ethics principles and operationalization

In Figure 25, the oval cluster illustrates that respect for persons is operationalized in voluntary, informed, and ongoing consent. The triangle cluster highlights that concern for welfare is operationalized in benefits vs. risks, privacy, and confidentiality. The rectangle cluster shows that justice is operationalized in recruitment, inclusion/exclusion, and research dissemination. The clustering also highlights how the principles are equally weighted in the research ethics process. Other considerations in the research ethics process include assessing and declaring any conflicts of interest, identifying research funding, assessing researcher experience with the proposed methods, and a scholarly review of the research plan.

4.2 Operationalized research ethics in the industrial re-design project

4.2.1 Respect for persons: Voluntary, informed, and ongoing Consent

The capacity to consent refers to "the ability of prospective or actual participants to understand relevant information presented about a research project, and to appreciate the potential consequences of their decision to participate or not participate" (Government of Canada, 2010, p. 3). In the study, the potential participants are all competent adults (if not, authorized third parties would be involved in the consent process).

To ensure free/voluntary consent, the company entered into the following agreement with participants and researchers in a letter of permission: "Employees who choose to take part in the study will be allowed to use paid work time to participate and this choice is voluntary with no influence on their employment" (excerpt, company letter). Additionally, it is important to note that there is no financial compensation or financial incentive offered to participants in the research study.

To ensure that consent is free of undue influence or coercion, the recruitment process is used to minimize and manage this. The recruitment process begins with a verbal, face-to-face engagement with potential participants at the manufacturing facility to describe the research study and invite them to participate (Figure 26).

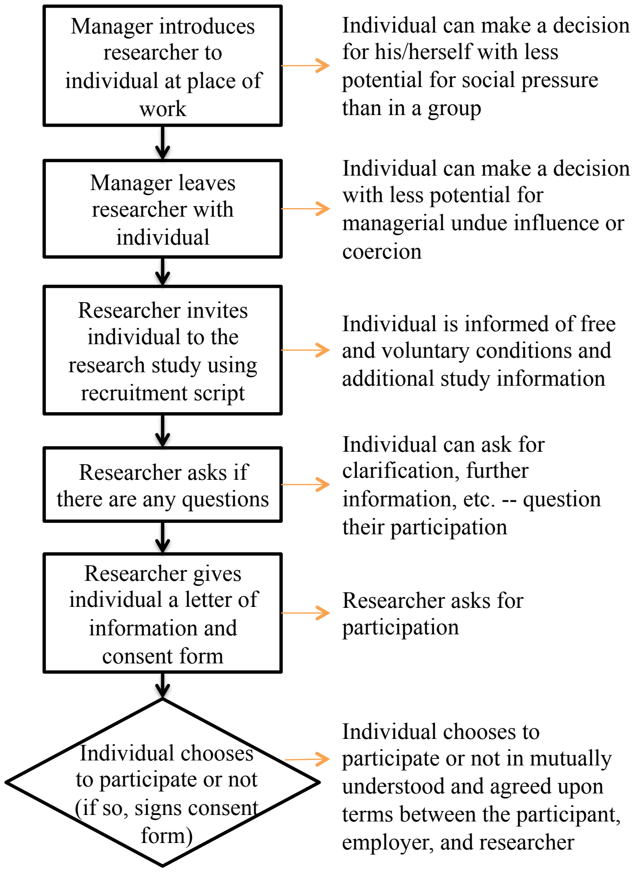


Figure 26: [Participant] recruitment process (study)

Undue influence and coercion is specifically managed in the recruitment process, Figure 26, by having the manager not present at the time the individual makes a decision to participate, and by approaching individuals one at a time who will not have social pressure to participate or not. This is supported by the company (manager) in the letter of permission: "I have agreed to help [the primary researcher] contact the potential participants in line with the recruitment strategy outlined in the Research Ethics Board application."

The recruitment script states the researcher's name and affiliation, motivations for the study, and the ability to withdraw from the study. The script also describes what involvement in the study will include:

> *If you choose to participate, you would be involved in the participatory design of the assembly process with other participants where we'd collectively analyze the process and work, look at opportunities and problems, create ideas and solutions, create prototypes of the design, select and implement a design, and then monitor*

how well the design works. Because this part of the research would be a group event, I cannot ensure complete confidentiality in this specific phase but I can ensure that I will keep your information confidential in this phase and all phase of the research. This research would also include me observing the assembly process and your work in limited time periods (no more than an hour at a time). If I'm observing, I will always inform you and confirm that I have your consent to observe (excerpt, recruitment script).

The consent process includes a consent form (signed by the participant) and a letter of information (for the participant's record) containing the following identical information:

- Purpose of the study,
- Research procedures,
- Potential risks and discomforts,
- Potential benefits to participants and/or society,
- Compensation,
- Confidentiality,
- Participation and withdrawal,
- Feedback of the results of the study to the participants,
- Rights of research participants, and
- Signature and contact information of the investigator.

This information helps to inform the participant in his/her decision-making, along with time to decide (e.g. a few days). To ensure ongoing consent, at all points of contact with the participants throughout the research study, the researcher verifies that the participant is consenting to the research and reminds the participant that s/he has the right to withdraw from the study at any time.

4.2.2 Concern for welfare: Risks vs. benefits, privacy, and confidentiality

For the study, the initial group vulnerability is assessed with no pre-existing physiological or health conditions, cognitive or emotional factors, socio-economic or health statuses characteristic of the participant group. The only known pre-existing vulnerability is institutional vulnerability because the participants are company employees and subject to the formal authority of their supervisor(s) in their workplace.

Herein lies the biggest challenge to the research study from a risk perspective. For the PD framework to yield useable and ethical results, unnecessary risk ought to be removed or managed. In complex STS it can be challenging to manage this risk, since it may involve many/conflicting system relationships. In PD, there are no known physical or psychological risks. There is the potential for economic risk since the research takes place at the participants' place of work. The economic risk could be related to 1) a loss of income while participating in the study and/or 2) the loss of a job.

To manage the economic risk, the company entered into an agreement with the participants and researcher, mentioned above. The company letter states that "Employees who choose to take part in the study will be allowed to use paid work time to participate and this choice is voluntary with no influence on their employment" (addressing economic risk 1 and 2 above). Additionally, the intention of the research is clearly stated in the recruitment and consent processes: to inquire into a participatory model where people are involved in redesigning their work and assembly process. In other words, the intent is not to re-design a process to eliminate jobs. This information is shared with participants in the recruitment process via the recruitment script, information letter, and consent form. In general, the research risks posed by PD in the study are summarized in Table 12.

Risk	Low	Medium	High
Physical risks	x		
Psychological/emotional risks	x		
Social risks		x	
Dual/multiple relationship with participants	x		
Data security	x		
Deception involved in study	x		

Table 12: Risk assessment (study)

The social risk is rated medium in Table 12 due to the challenges in privacy and confidentiality. Since participatory design is synonymous to an extended group event, and participant bystanders and non-participant bystanders in the production area of the facility can see the design work taking place, confidentiality and privacy cannot be guaranteed in this specific phase of the research study. In the context of the research, however, this does not pose a significant risk because these are the typical work conditions of the environment. Nevertheless, the risk is managed by being forthright and honest – attributes not uncommon to professional engineers – with participants about these limitations in the recruitment and consent processes. The data is managed as shown in Figure 27.

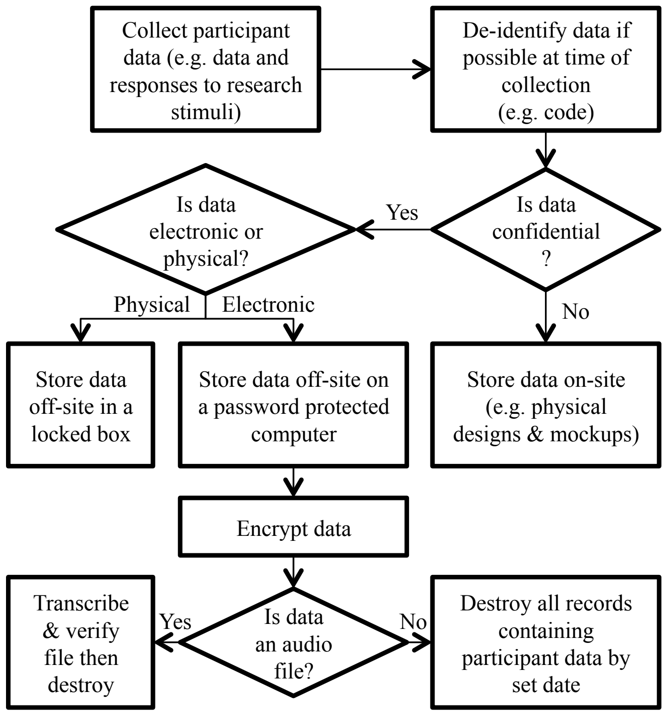


Figure 27: Data management process (study)

The direct benefits to participants in the research study include the opportunity to gain knowledge and information on the design of their work in the assembly process. Also, "Participatory design is meant to empower workers' quality of life both in terms of democratic empowerment (that is, workers' control over their own work organization, tools, and processes) and functional empowerment (that is, workers' ability to perform their given tasks with ease)" (Spinuzzi, 2005, pp. 7, 8). Participants may learn new knowledge and skills and may choose to apply them in the workplace and other chosen applications. Indirectly, the participants can take an active role in defining this participatory orientation in emerging research.

4.2.3 *Justice: Inclusion vs. exclusion, recruitment, and results dissemination*

The inclusion principle defines who *will*, and *will not,* be included in the research study. For the study, the inclusion principle is defined as: a person who works, directly or indirectly, with the assembly process being studied at the company (pictured in the high-level process diagram, Figure 28).

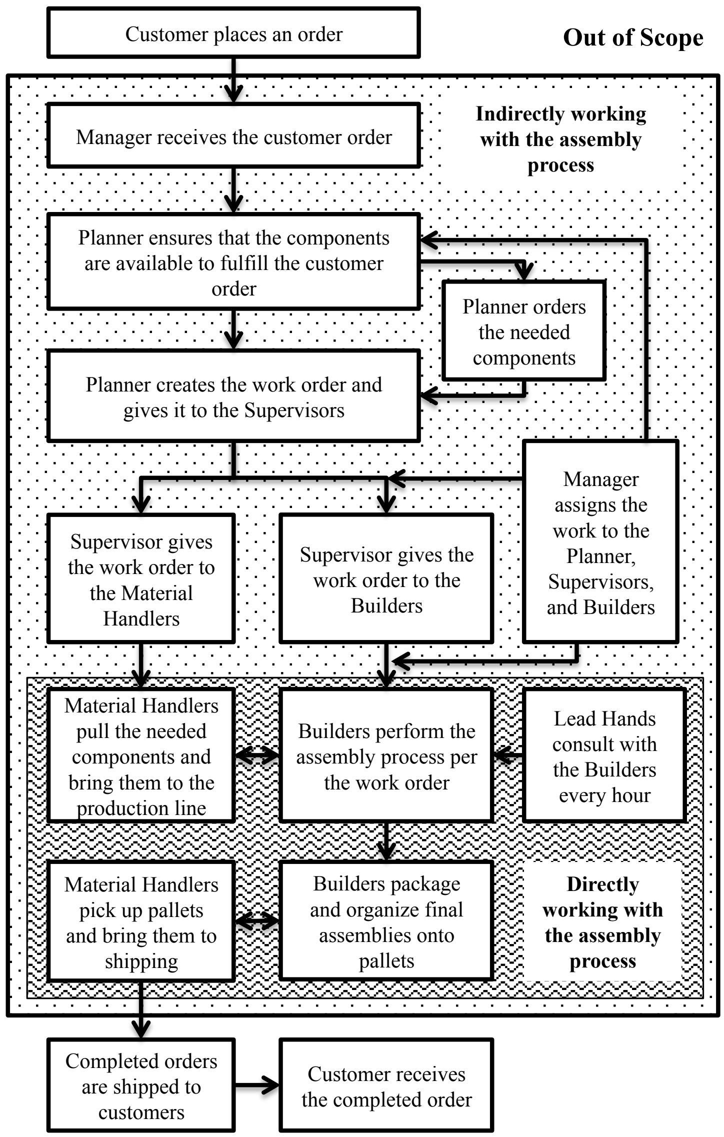


Figure 28: Participatory inclusion principle for the assembly process (study)

Figure 28 illustrates that the inclusion criterion includes people who work both directly and indirectly with the assembly process. While the primary focus of the research study is on the assembly process (direct involvement), inter-relationships with the preceding and following steps are recognized as part of a larger system (indirect involvement). In this vein, the process and context are viewed as a socio-technical system.

In the study, the potential participant pool includes up to 7+ potential participants (u-unionized workers and m-management) including: planner (m), supervisor (m), manager (m), lead hand (u), builder (u), and material handler (u). At the onset of the research study, eight participants are recruited representing the roles from the participant pool above.

The only role not represented in the recruited participants is the material handlers, for whom it proved to be difficult to discern how to apply the inclusion principle. In the manufacturing facility in the study, there are over 20 material handlers with additional temporary workers. One material handler is assigned to the assembly process; however, this position rotates weekly. Therefore, the potential participant pool grew significantly with this information, while the relationship between the assembly process and each material handler became more sporadic and less pertinent. It also became significant to recognize the role of the lead hands with respect to material handling work. Prior to becoming lead hands, each lead hand worked as a material handler. In many cases, the lead hands also continue to share work with the material handlers (e.g. operating forklifts to bring materials to and from the assembly process). With this information in mind, it was decided that the material handlers would not be included in the recruitment and that the researchers would engage the lead hands in perspectives on material handling. In addition, many of the builders are temporary workers who participate and withdraw at various stages of the research. In turn, recruitment is an ongoing process.

The results at the beginning of the research study are displayed on a bulletin board at the manufacturing facility and discussed with participants in person. Participants are also invited to attend a presentation at the manufacturing facility, with a question and answer period and a one-page summary of the results, at the end of the multi-phase study. The company letter of support indicates support for this presentation, inviting participants and non-participants to attend. The dissemination of research results is designed to meet the participants' needs. [For further research ethics details on this research, please see the appendices (Appendix A – Recruitment script; Appendix B – Consent form; Appendix C – Letter of information; Appendix D – Consent for audiotaping).]

4.3 Professional engineering ethics

Next, the research ethics framework is related to a professional engineering code of ethics. For the purpose of this study, the Professional Engineers of Ontario (PEO) code of ethics is utilized, which is found in Section 77 of the Ontario Regulation 941 under the Professional Engineers Act (PEO, 2011). The alignment between engineering professional practice and research ethics is correlated and presented in Table 13.

Research ethics principles	Operationalized in the research ethics process*	Operationalized in professional engineering practice+
Respect for persons	Voluntary, informed, and ongoing consent	"Fidelity to public needs" (77(1ii))
		"Devotion to high ideals of personal honour and professional integrity" (77(1iii))
Concern for welfare	Benefits vs. risks (including privacy and confidentiality)	Confidentiality (77(3))
		"Regard the practitioner's duty to public welfare as paramount" (77(2))
Justice	Inclusion vs. exclusion, recruitment, and research dissemination	"Fairness and loyalty to the practitioner's associates" (77(1i))
		"Devotion to high ideals of personal honour and professional integrity" (77(1iii))

Table 13: Aligning core principles of participation from research to practice

* Canadian Tri-Council Policy Statement on Research Ethics (Government of Canada, 2010)
\+ Professional Engineers Ontario (PEO) Code of Ethics (2011, p. 77)

In addition to Table 13, there is also a clause in the engineering code of ethics regarding disclosing any conflict of interest, Section 77(4) (PEO, 2011), which is also integral to research ethics. In Table 13, it is noted that there are specific clauses in the PEO code of ethics related to concern for welfare ("duty to public welfare") and justice ("fairness and loyalty to the practitioner's associates"). Respect for persons is not explicitly stated, though one could argue that it could be implied within "personal honour and professional integrity" and "fidelity to public needs." This alignment highlights that the ethical considerations for participation in research align with the engineering code of ethics while also introducing new perspectives for consideration, e.g. accenting respect for persons and making the meaning of this explicit, to fully enable participation with an ethical understanding and practice.

4.4 Synthesizing the ethical roadmap: Aligning research, professional, and participatory design ethics into ethical considerations

The ethical considerations in research and engineering practice are further [aligned with the ethical considerations in the PD literature. These three perspectives are synthesized into the developed questions for ethical consideration in participatory socio-technical system re-design] in Table 14.

Research ethics principles	Operation-alized in research ethics*	Operation-alized in professional engineering practice+	Questions for ethical consideration in participatory socio-technical system re-design	Ethical questions in the PD literature (Robertson and Wagner, 2013)
Respect for persons	Voluntary, informed, and ongoing consent	“Fidelity to public needs” (77(1ii)) “Devotion to high ideals of personal honour and professional integrity” (77(1iii))	• How will the potential participants be informed about the project? • What relevant information should be shared with potential participants (e.g. problems, questions, goals, methods, procedures, timeline, incentives, risks, benefits, etc.)? • Will there be compensation offered to participants? • How will people choose to participate or not? • Can the participation be voluntary (free from coercion or undue influence)? How?	“What can we offer participants? ” (Robertson and Wagner, 2013, pp. 77–78) “How do we engage with participants? ” (Robertson and Wagner, 2013, pp. 72–75)
Concern for welfare	Benefits vs. risks (including privacy and confident-iality)	Confidentiali ty (77(3)) “Regard the practitioner’s duty to	• What are the potential benefits to the participants, organization, industry, and society? Are these direct or indirect? E.g. empowerment, quality of life, knowledge sharing and	

		public welfare as paramount" (77(2))	development, etc. • What are the risks involved in the project? E.g. economic (employment) and social (group event with limited confidentiality and privacy). • What vulnerabilities exist for the participants? • What impact might the risks have on the participants and organization? • How can the risks be minimized and/or managed? What cooperation from the employer is needed? • Do the benefits outweigh the risks? • Who will have access to the data and in what form? • How will the data be managed?	
Justice	Inclusion vs. exclusion, recruitment, and research dissemina-tion	"Fairness and loyalty to the practitioner's associates" (77(1i)) "Devotion to high ideals of personal honour and professional integrity" (77(1iii))	• Will the participants be treated with equal respect and concern for their welfare (equity)? • Will the benefits and burdens be fairly distributed amongst the participants? • Are there vulnerable circumstances that exist? • What contextual conditions exist, to ensure that vulnerable circumstances are not created? • How will the potential participants be asked to participate? Will there be multiple steps? Who will be present (or not present)? • How will the results be communicated with participants so that they know what they've helped to accomplish? Will a face-to-face presentation with Q&A	"Who do we engage with in a participatory design project?" (Robertson and Wagner, 2013, pp. 71–72)

			be helpful? • Who will be included (and excluded) as a participant and why? How does this rationale align with the project's purpose? Will there be considerations for temporary, shift, or rotating work?	

Table 14: Aligned ethical considerations for participation in research, engineering practice, and participatory design

* Canadian Tri-Council Policy Statement on Research Ethics (Government of Canada, 2010)
+ Professional Engineers Ontario (PEO) Code of Ethics (2011, p. 77)

The questions for ethical consideration in Table 14 are intended to encourage inquiry into the ethical practice underlying and supporting participation in context, whether utilizing PD or considering participation in a broader socio-technical perspective.

4.5 Discussion and conclusions

This chapter develops a roadmap of ethical considerations in the participatory re-design of a socio-technical system. The roadmap is grounded in participatory ethics with three internationally recognized principles of research ethics: respect for persons, concern for welfare, and justice. The operationalization of the research ethics principles is demonstrated with examples from the re-design industrial project at hand, the re-design of an assembly production system and socio-technical system archetype. This operationalization shows how the concepts can be implemented pragmatically e.g. in the recruitment process, management of risks (such as economic risk), inclusion principle, etc. A professional engineering code of conduct (PEO O.Reg. 941) is then aligned, highlighting how the research ethics principles align with fidelity to public needs, personal honour, professional integrity, confidentiality, duty to the public, and fairness. At the same time, the alignment shows that participation accents respect for persons e.g. in the demonstration of voluntary, informed, and ongoing participant consent. Ethical questions posed in the PD literature are then aligned: Who participates? How? What can we offer? The three ethical perspectives -- research, professional engineering, and PD ethics -- are synthesized into ethical considerations in the form of questions.

These ethical considerations, their development, and their demonstrated implementation comprise an ethical roadmap for the participatory re-design of a socio-technical system. The ethical considerations provide specificity to the broader ethical questions posed in the participatory design literature. E.g. "Who participates?" can be answered by borrowing the inclusion principle concept from research ethics to clearly define who is included, who is not, and why. This serves to create greater transparency and fairness, which support the ethical foundation of PD. In this study, the inclusion principle also highlights why both management and non-management participants are important to include. This consideration contrasts the earlier PD literature, which focused on primarily empowering non-management workers. The roadmap, therefore, synthesizes the three ethical perspectives of research, professional engineering, and participatory design ethics to build a layered ethical understanding in situ.

By making evident the relations between the three perspectives of research, professional engineering, and participatory design ethics, the roadmap moves from the current research context to orient future researchers, engineers, and/or participatory design practitioners in navigating the ethical considerations involved in participation, participatory design, and the participatory re-design of a socio-technical system. In this vein, engineering researchers and practitioners (including consultants) can design their own appropriate routes in relation to the developed ethical roadmap. They can relate the roadmap to their PD projects and STS contexts with an informed conceptual and practical understanding of the ethical considerations for participation, which is fundamental to the practice of PD. The limitations of this chapter research are examined in Chapter 12; the trustworthiness and validation of this chapter research are evaluated in Chapter 11.

When implemented, the ethical considerations result in informed and voluntary participants in the re-design project; established trust between the researchers and participants; set mutual expectations for the participants, researchers, and company; and a foundation for data reliability. Based on these conclusions, "Ethical considerations for participation" is the first step in this dissertation's model for re-designing a socio-technical system, summarized systematically with an IDEFO model in Figure 29. Figure 29 is related to the research questions in the dissertation study as follows. The inputs and mechanisms relate to research question 2 (shown in Figure 29 in `Courier font`). The questions, outputs, and constraints relate to research question 3 (shown in Figure 29 in Calibri font).

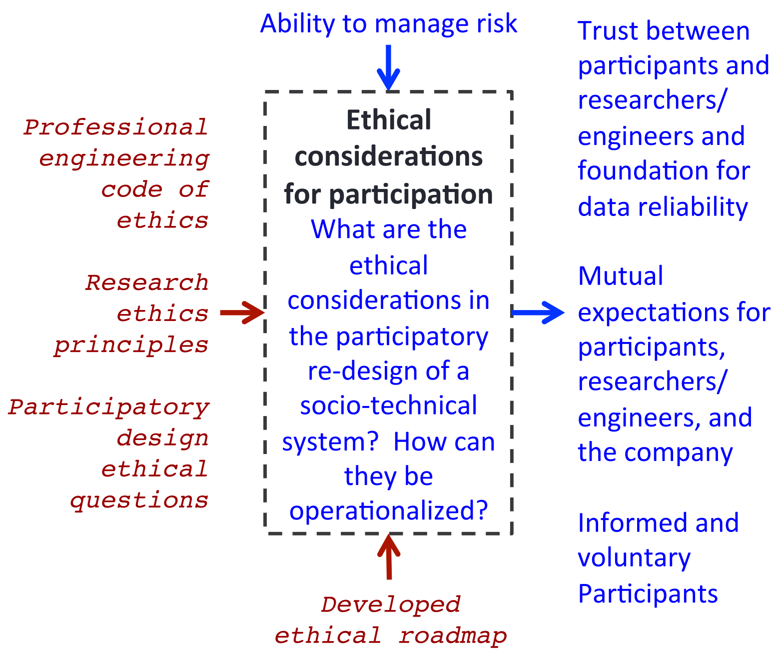


Figure 29: Ethical considerations IDEF0

The position of "Ethical considerations for participation" (Figure 29) in this dissertation's model for re-designing a socio-technical system is shown in Figure 30.

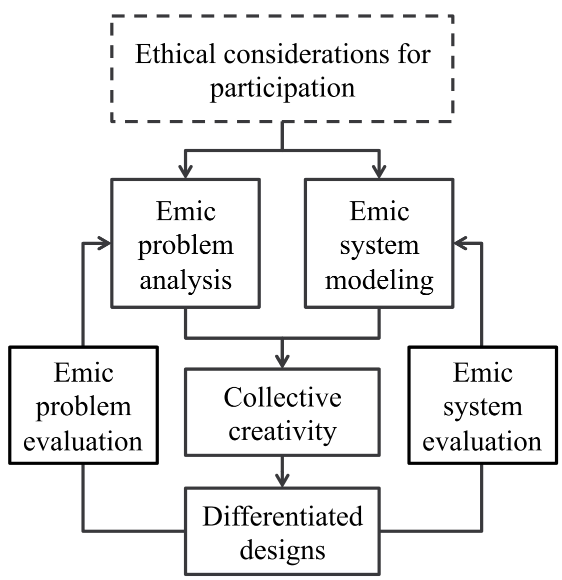


Figure 30: Ethical considerations in the developed model for re-designing a socio-technical system

5 Emic problem analysis in socio-technical system re-design

After establishing the ethical considerations for participation (Chapter 4), the next step in developing a participatory approach for re-designing a socio-technical system is to define the problem. Problem definition is positioned early in engineering design methodology (Pahl et al., 2007, p. 16) and systems design methodology (Whitten and Bentley, 2007, p. 30), and both describe design generally as a problem solving process. Problem analysis has not been explicitly related to STS theory in re-design (Table 5).

In turn, the research in this chapter asks: How can the problem be defined in socio-technical system re-design? What is the re-design problem in the STS re-design project at hand? This chapter investigates these questions with an etic (outsider) approach and an emic (insider/participant) approach. The latter perspective grounds the research in qualitative methodology (§3.2) and develops the descriptive study I of design research methodology (§3.1, Figure 6). The intention here is to explore this chapter's research questions *in situ* in the re-design of an assembly production system and socio-technical system archetype. The industrial context and participants are described in detail in §3.4. Both approaches begin with understanding the current assembly production system (its current design) but their means, perspectives, and outcomes differ.

The etic approach in §5.1 is a typical industrial or manufacturing engineering approach and asks, "What is the re-design problem? And how can it be defined?" from an outside perspective via engineering knowledge and practice that exists outside the re-design context. The approach begins by performing statistical analysis on production data. The results of the statistical analysis (§5.2.1) are used to inform an understanding of the causes (x's) affecting the primary function (Y) of the socio-technical system. The primary function of the socio-technical system, as discussed in §2.6, is defined by Emery (1989) as economic productivity, the transformation of inputs into outputs (Pasmore, 1988). In an assembly production system, the primary function is measured as cycle time, the rate at which process inputs are converted into a final assembly output.

In contrast, the emic approach in §5.1 is integral to qualitative methodology, as discussed in §3.2.2, and asks, "What is the re-design problem? And how can it be defined?” from an inside perspective via the socio-technical system operator participants within the re-design context. The approach developed here begins by interviewing participants (n=8). Participants are asked to describe (1) the current assembly process and their work with it, and (2) the ideal assembly process and their work with it, engaging idealized design (Ackoff, Magidson, and Addison, 2006). The gap or tension between the current and ideal state is considered the problem. The interviews are then transcribed and coded with an open coding technique to identify various issues. The results of the coding (§5.2.2) are then mapped to the phases of the assembly process and grouped into themes. This visual map is analyzed with graph theory and adapted usability analysis, which analyzes the issues and helps to form the emic problem statement. This investigative approach is grounded in participation and adapts industrial engineering techniques to analyze the emic perspective (graph theory and a usability plot).

This synthesized emic investigative approach addresses the need that Bley et al. (2004) identify, to bridge participative approaches with the work of industrial engineers in designing assembly production systems (p. 498). Since workers manage the complexity of assembly operations with efficiency (Hu et al., 2011, p. 726), the emic investigative approach also provides a means to analyze complex STS problems with operator participants adding to the literature on manufacturing system complexity (ElMaraghy et al., 2012; ElMaraghy and Urbanic, 2004). In this dissertation, the developed emic investigative approach supports emic problem analysis in a model and framework for re-designing a socio-technical system (§5.3).

In this chapter, the primary ideas and section §5.2 (including tables, figures, equations, and excerpts) are taken from the paper, “Complexity Analysis for Problem Definition in an Assemble-to-Order Process: Engaging Emic and Etic Perspectives” (Townsend and Urbanic, 2014). Titles have been changed to align with this dissertation; any wording additions are indicated with square brackets. This conforms to the Elsevier CIRP Procedia copyright agreement and clearances in Appendix N.

5.1 The emic and etic problem analysis investigative approaches

The emic investigative approach is outlined in Figure 31 and the etic in Figure 32.

Recruit participants and operationalize the ethical consideration	• See Chapter 4, the operationalized inclusion principle here engages people who are directly and indirectly involved in the assembly process, engaging a system perspective in problem analysis • 8 participants took part in the pre-interview in the roles of manager, planner, builder, lead hand, and supervisor

Conduct and record the pre-interviews	• Record pre-interviews with participant consent (see Appendix D)
	• Pre-interview asks:
	  • How would you describe the current assembly process? How would you describe your work with the current assembly process?
	  • How would you describe an ideal assembly process? How would you describe your ideal work with an ideal assembly process?

Transcribe the pre-interview recordings	• Transcript accuracy is verified by reading the transcript while listening to the audio recording
Code the transcripts with emic or open coding	• Identify codes by reading each transcript and highlighting each idea. If a code is common to more than one interview, care is taken to ensure that the ideas share similar meaning by using a code book. The code book includes the code with a definition and quote(s) from the interview(s). • Codes with broad commonality are grouped into themes
Identify the participants' main phases of the assembly process on a plot	• In the transcripts in this study, the participants described four phases of the assembly process that were organized as four quadrants on the plot
Map codes to the plot (assembly process phases)	• The codes are considered nodes (bubbles) and are plotted in relation to one another and the four quadrants of the plot • This creates a complex web that resembles graph theory
Analyze the complex web with graph theory	• Create a magnitude matrix of the code occurrence (Mji) • Create an adjacency matrix of the relationships between codes(Aij) • Create a weighted adjacency matrix that captures each code's relationship with other code magnitudes, considering the significance of relationships in the code web as a whole (Wji)
Prioritize the codes into problem foci using adapted usability analysis	• Specific problem analysis foci are identified through a plot of weighted adjacency versus magnitude, an adaptation of a usability plot (Nielson, 1994; Lehto, 2013) • The code's weighted adjacency is considered the problem severity and the code's magnitude is considered the number of people affected by the problem
Create an emic problem statement	• An emic problem statement is formed based on a format used in design thinking (Britos Cavagnaro, 2013) • This integrates the codes, prioritized codes, and themes

Figure 31: The investigative approach for emic problem analysis

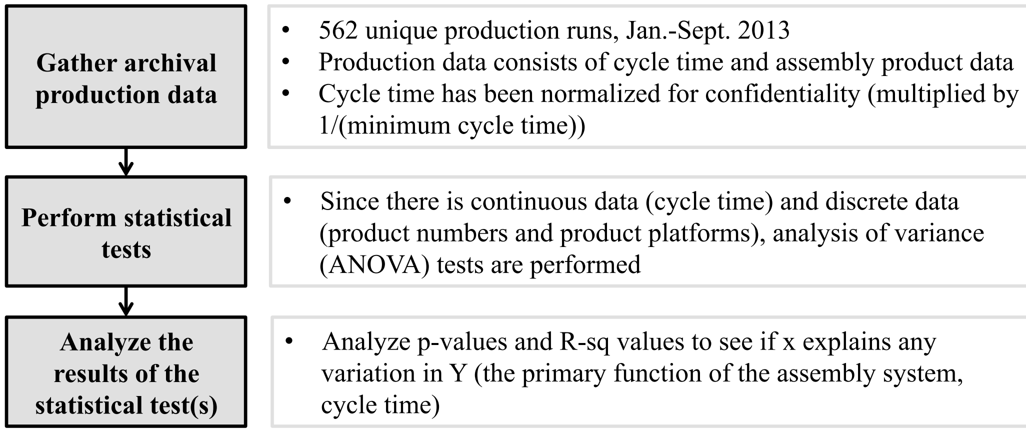


Figure 32: The investigative approach for etic problem analysis

The results of the etic and emic investigative approaches for problem analysis, Figure 32 and Figure 31, are found respectively in §5.2.1 and §5.2.2.

5.2 Results

5.2.1 Results of the etic investigative approach for problem analysis

The ANOVA tests use the following nomenclature:

- DF Degrees of freedom
- SS Sum of squares
- MS Mean squares
- F F-statistic (signal to noise ratio)
- P P-value or probability value
- R-Sq R-squared value (% of variation in Y explained by X)
- H_o Null hypothesis
- μ Mean cycle time [minutes/assembly]

A one-way ANOVA test is performed for cycle time versus product number using a 95.0% confidence level to test the null hypothesis in Equation 1. In this data set, there are 268 unique product numbers (final assemblies), of which 154 are manufactured only once in the data set time frame of 9 months. These are excellent conditions to test the impact of product variety on the productivity [cycle time] for a manual assembly process.

Results are shown in a box-plot (Figure 33) and a standard ANOVA analysis table (Table 15).

$$H_o: \mu_{product\ 1} = \mu_{product\ 2} = \cdots \mu_{product\ 268} \qquad \text{Equation 1}$$

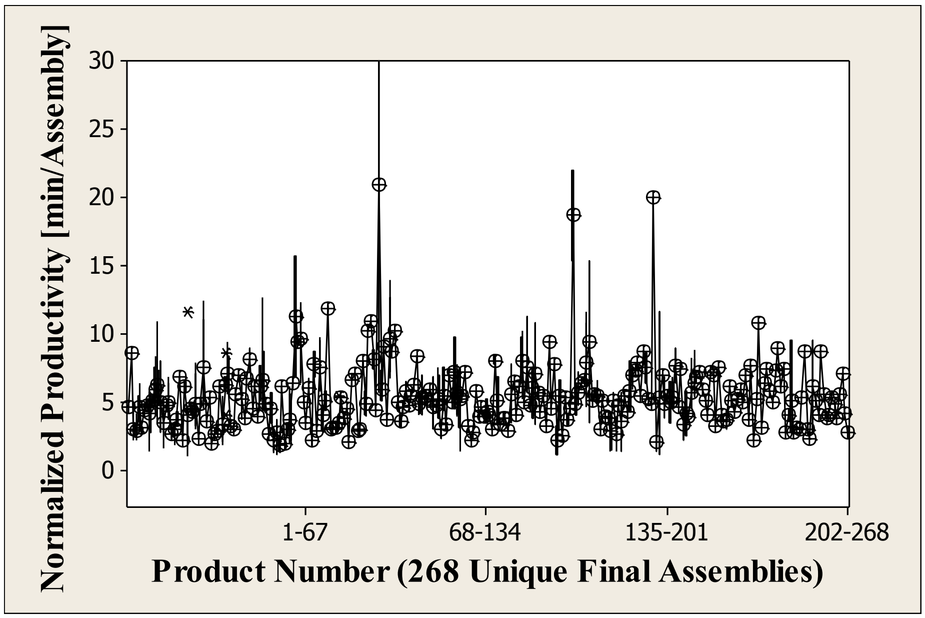


Figure 33: ANOVA boxplot on cycle time vs. product number

Source	DF	SS	MS	F	P
Product Number	267	3900.6	14.6	1.28	0.021
Error	295	3377.5	11.4		
Total	562	7278.1			
R-Sq = 53.59%					

Table 15: ANOVA table on cycle time vs. product number

Table 15 indicates that the p-value is 0.021, which is <0.05; therefore, the null hypothesis is rejected. Thus, not all of the [mean cycle times] are the same for every product (though there may be some means that are statistically similar). This is not surprising; however, the R-Sq value is interesting in stating that only 53.59% of the variation in [cycle time] can be explained by the different product numbers. To further explore this, product families are tested based on common platforms using the same analysis set-up with the null hypothesis in Equation 2. Results are shown in a box-plot (Figure 34) and a standard ANOVA analysis table (Table 16).

$H_o: \mu_{platform\ 1} = \mu_{platform\ 2} = \cdots \mu_{platform\ 8}$ Equation 2

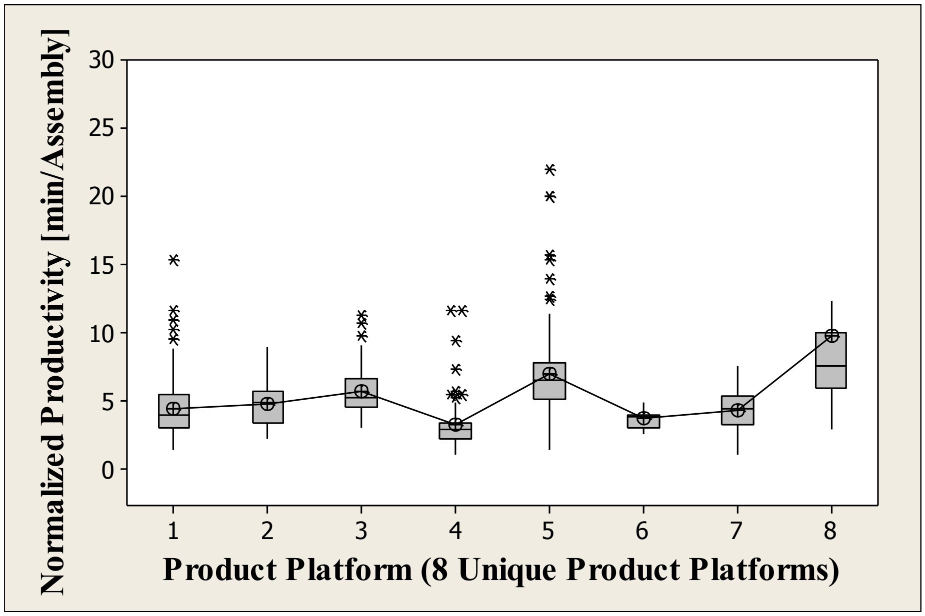


Figure 34: ANOVA boxplot on cycle time vs. product platform

Source	MS	SS	MS	F	P
Product Platform	7	1511.6	215.9	20.78	0.000
Error	555	5766.5	10.4		
Total	562	7278.1			
R-Sq = 20.77%					

Table 16: ANOVA Table on cycle time vs. product platform

Table 16 indicates that the p-value is <0.001, which is <0.05; therefore, the null hypothesis is rejected. Thus, not all of the [mean cycle times] are the same for every product platform (though there may be some means that are statistically similar). This is not surprising; however, the R-Sq value is interesting in stating that only 20.77% of the variation in [cycle time] can be explained by the different product platforms.

What this analysis lends itself to is the following question: if product variety itself only accounts for 53.59% of the [cycle time] variation, and product platforms even less so with 20.77%, then the problem of responding to product variety in this assemble-to-order process has influences beyond that of analyzing product complexity and its relationship with the assembly process and manufacturing system. These other influences on complexity in the assembly system need to be understood; consequently, in this research study, knowledge workers who experience this complexity every day in their work with the assembly process are asked to participate in sociotechnical problem analysis.

5.2.2 Results of the emic investigative approach for problem analysis

In the pre-interview [n=8], questions 4 – 7 asked each participant to describe the current and ideal assembly process and his/her work with both. By emic coding of the transcripts, 26 codes emerged as participant-defined areas of concern (cf. code nomenclature).

Code Nomenclature:

1 Respond to order volume growth
2 Accurate forecasting
3 Forecasting feedback
4 Steady workforce of builders
5 Efficient staffing of builders
6 Consistent relationship with builders
7 Ease of lead hand and builder communication
8 See builders
9 Training builders
10 Establish builder responsibility and autonomy
11 Ensure quality of final assemblies (no post-inspection)
12 Working with limited room and space
13 Organize and designate position for materials (staging)
14 Improve flow
15 Streamline assembly process, more efficient
16 Flow like an assembly line
17 Assembly line differentiation (contextualized)
18 No need for machines in assembly process
19 Improve build sequence and division of work
20 Builders set pace
21 Determine the right number of builders for tasks

22 Have a partner for builders
23 Working smarter not harder
24 Training for material handlers and lead hands
25 Conflicting flow and work for material handlers with the receiving work
26 Conflict for material handlers – getting supplies and putting away finished assemblies

These 26 codes are each identified by a bubble in Figure 35, with the code number in the middle. The size of the bubble represents the code occurrence; the scale is shown in the legend, for one and two occurrences. The codes are arranged relative to the four main phases of the production process: (1) Initiate the order (receive customer order and initiate work order); (2) Prepare for the assembly process; (3) Perform the assembly process; and (4) Finalize the order (close work order and request customer feedback). These phases represent four quadrants in Figure 35. The relationships between the emic codes (code to code) and the production phases (code to quadrant(s)) [described in the interviews] determine the position for the code in Figure 35 [placed by the researcher/engineer]. For example, layout (code 12) affects preparing for the assembly process (phase 2) with respect to staging materials (code 13) and also performing the assembly process (phase 3) with respect to improving flow (code 14). Thus, the codes form an interconnected web with each other and the main phases of the production process for problem analysis. Phases 2 and 3 are in scope for this research; phases 1 and 4 highlight context from initiating an order with a customer to finalizing an order. Through this mapping technique, prominent codes emerge not only for their occurrence (bubble size) but also for their interconnectedness (bubble proximity) and thematic relationships (bubble clusters). The latter enables problem focus areas to emerge (bubble shading), which are process, layout, and training.

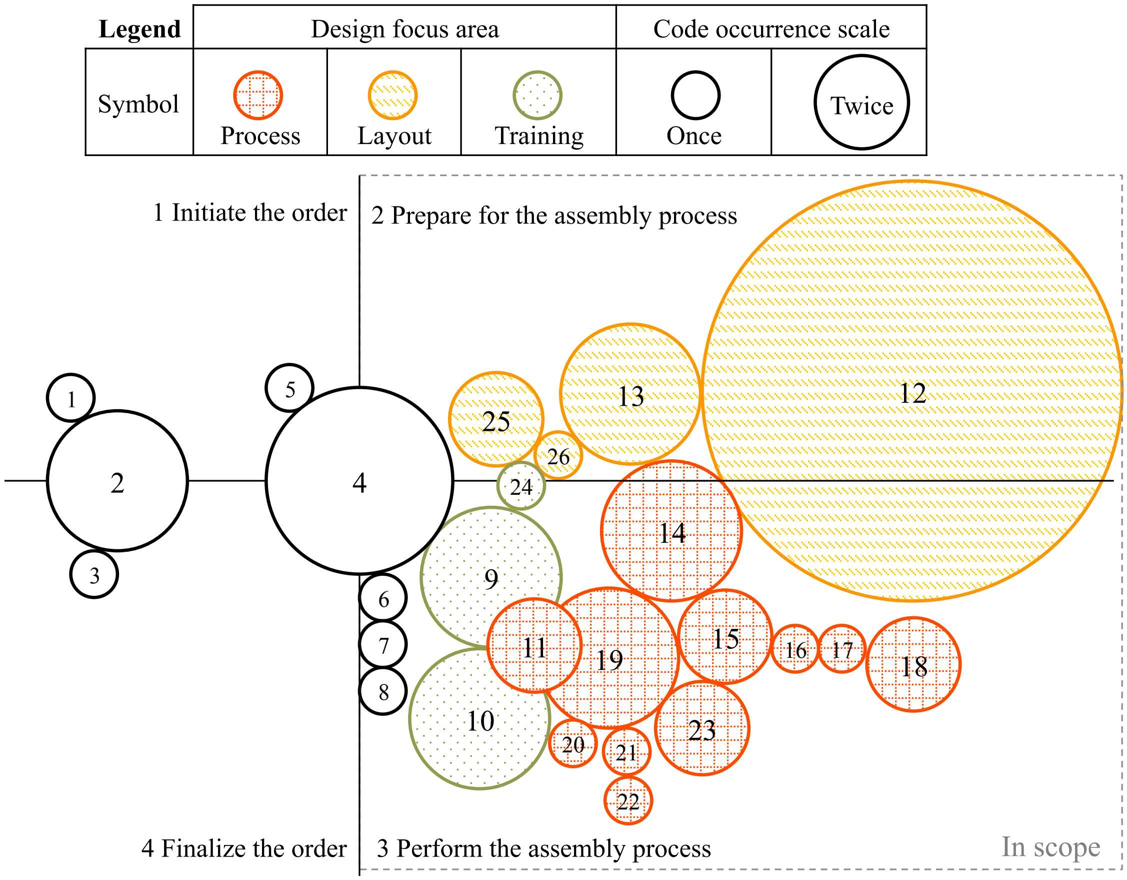


Figure 35: Map of emic coding to the four main phases of the assembly process (colour adaptation of (Townsend and Urbanic, 2014))

To further analyze the emic codes from the interview to define specific problem foci, graph theory is applied to the mapping in Figure 35 with the following nomenclature.

Graph Theory Nomenclature

G	Graph (Figure 4), undirected, not complete
N	Nodes (codes), |N| = 26
V	Edges (relationship, or connecting [surfaces of] two codes [circles in Figure 35]), E {(1,2), (2,3), (4,5), (4,6), (4,9)…}, |E| = 30
$\mathbf{A}_{ii}$	Adjacency diagonal matrix, where i = |N| = 26
$\mathbf{M}_{ji}$	Magnitude row matrix, where j=1, i=26
$\mathbf{W}_{ji}$	Weighted adjacency row matrix, where j=1, i=26
μ_M	Mean value in the magnitude matrix
μ_W	Mean value in the weighted adjacency matrix

Applying this nomenclature to the graph in Figure 35 using Equation 3 results in the diagonal adjacency matrix ($\mathbf{A}_{ij}$) in Figure 36 – akin to a design structure matrix (DSM). The sum for each row and column is stated at the end of the row and column; sums greater than the mean are highlighted in grey.

$$G = (N, E) \qquad \text{Equation 3}$$

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	
1	0	1																									1
2	1	0	1																								2
3		1	0																								1
4				0	1	1			1																		3
5				1	0																						1
6				1		0	1																				2
7						1	0	1																			2
8							1	0																			1
9				1					0	1	1													1			4
10									1	0	1								1								3
11									1	1	0								1								3
12												0	1	1													2
13												1	0	1												1	3
14												1	1	0	1				1								4
15														1	0	1			1				1				4
16															1	0	1										2
17																1	0	1									2
18																	1	0									1
19										1	1			1	1				0	1	1		1				7
20																			1	0							1
21																			1		0	1					2
22																					1	0					1
23															1				1				0				2
24									1															0	1	1	3
25																								1	0	1	2
26													1											1	1	0	3
	1	2	1	3	1	2	2	1	4	3	3	2	3	4	4	2	2	1	7	1	2	1	2	3	2	3	

Figure 36: Adjacency matrix (Aij) for the graph in Figure 35

Additionally, a row magnitude matrix ($\mathbf{M}_{ji}$) can be created for each code based on the code's occurrence in the interviews, shown in the second row in Figure 37 with values $\geq \mu_M$ highlighted. Applying Equation 4 creates a weighted adjacency matrix ($\mathbf{W}_{ji}$) based on the relationship between each code and the magnitude of the related code. $\mathbf{W}_{ji}$ is shown in the third row in Figure 37 with values $\geq \mu_W$ highlighted.

$$W_{ji} = M_{ji} \times A_{ii} \qquad \text{Equation 4}$$

Each code's magnitude and weighted adjacency value from each corresponding matrix are plotted on the [adapted] usability curve (Figure 38) relative to a critical point defined as (μ_M, μ_W) = (2,6). Critical codes are marked with an X in Figure 37.

Code	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26
Mij	1	3	1	4	1	1	1	1	3	3	2	9	3	3	2	1	1	2	3	1	1	1	2	1	2	1
Wij	3	2	3	5	4	5	2	1	10	8	9	6	13	17	9	3	3	1	14	3	4	1	5	6	2	6
Critical									X	X	X	X	X	X	X				X							

Figure 37: Magnitude matrix, weighted adjacency matrix, and critical codes

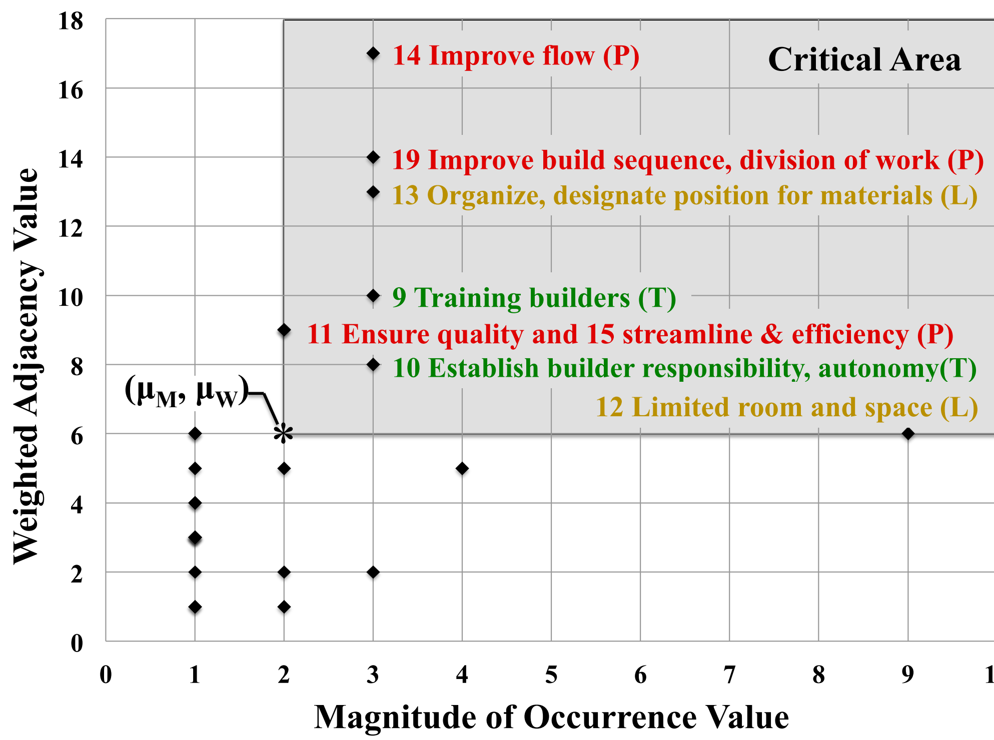


Figure 38: Critical codes, weighted adjacency vs. magnitude occurrence and code's primary relation to P-Process, L-Layout, or T-Training (colour adaptation of (Townsend and Urbanic, 2014))

The critical codes, or critical problem foci, identified through the graph theory analysis and usability plot in Figure 38 relate to the previously defined problem focus areas as follows: four foci relate to process (codes 14, 19, 11, and 15), two foci relate to layout (codes 12 and 13), and two foci relate to training (codes 9 and 10). In turn, the following emic problem statement is formed: the stakeholders (builders, lead hands, supervisor, planner, and manager) need a re-designed assembly process "that applies to us" with a focus on process, layout, and training because of eight critical problem foci and the related 26 concern web.

5.3 Discussion and conclusion

This chapter compares etic and emic investigative approaches for problem analysis in socio-technical system re-design.

The etic investigative approach, Figure 32, utilizes typical industrial engineering methods to answer the questions "What is the re-design problem? And how can it be defined in a socio-technical system re-design?" from an outside perspective via engineering knowledge and practice that exists outside the re-design context. The etic approach statistically analyzes archived production data to explain the problem as the causes affecting variation in cycle time, a measure of the primary function of the assembly (socio-technical) system. Here, ANOVA analysis found that product number (R-sq = 53.6%; p-value = 0.021; 95% confidence interval) and product platform (R-sq = 20.8%; p-value < 0.001; 95% confidence interval) affected variation in cycle time, analyzing 562 data events (unique production runs). While these findings highlight that these factors affect variation in cycle time, a measure of the primary function of the assembly and socio-technical system, they also indicate that the re-design problem goes beyond analyzing the relationship between product complexity and cycle time variation (the R-sq values are not 100%). This etic approach does not highlight what these additional underlying issues might be, but the emic approach does by uncovering a web of connections in the assembly production system.

The emic investigative approach, developed in Figure 31, integrates qualitative methods with adapted industrial engineering techniques to answer the questions "What is the re-design problem? And how can it be defined in a socio-technical system re-design?" from an inside perspective via the socio-technical system operator participants within the re-design context. The emic approach utilizes a developed combination of emic coding, visual mapping, graph theory, and an adapted usability plot to analyze participant pre-interview transcripts to explain the problem as the tension between the current and ideal operation of the assembly process. Here, 8 participants were recruited with the ethical considerations outlined in Chapter 4. The 8 participants, representing management and non-management roles, took part in pre-interviews where they described the current assembly process and their work with it as well as the ideal assembly process and their work with it. The interview recordings were transcribed and coded to reveal a visual mapping of 26 emic codes/issues and three problem focus areas/themes (process, layout, and training) in relation to re-designing the assembly production system. By analyzing this web of participant concerns with graph theory (magnitude, adjacency, and weighted adjacency matrices) and an adapted usability plot, the 26 codes were further refined into eight critical problem foci. These critical issues align with the process (4), layout (2), and training (2) problem focus areas/themes. The analysis was then synthesized into the following emic problem statement for the re-design project at hand: the stakeholders (in the roles of builder, lead hand, supervisor, planner, and manager) need a re-designed assembly production system "that applies to us" with a focus on process, layout, and training because of eight critical problem foci and the related 26 concern web.

The developed investigative approach for emic problem analysis results in an emic problem statement and emic problem reference model (26 concern web, 8 critical issues, and 3 themes) in the re-design of a socio-technical system and the re-design of the assembly production system at hand. This problem statement and emic problem reference model inform co-design (Chapter 7) and provide a means and basis to evaluate the co-design impact in before versus after comparison (Chapter 10). The trustworthiness and validation of this chapter research are evaluated in Chapter 11. The limitations of this chapter research are examined in Chapter 12.

Based on these conclusions, "Emic problem analysis" is a critical step after "Ethical considerations for participation" (Figure 29, Chapter 4) in this dissertation's model for re-designing a socio-technical system, summarized systematically with an IDEF0 model in Figure 39. Figure 39 is related to the research questions in the dissertation study as follows. The inputs, mechanisms, and reference models relate to research question 2 (shown in Figure 39 in *Courier font*). The questions, outputs, and constraints relate to research question 3 (shown in Figure 39 in Calibri font).

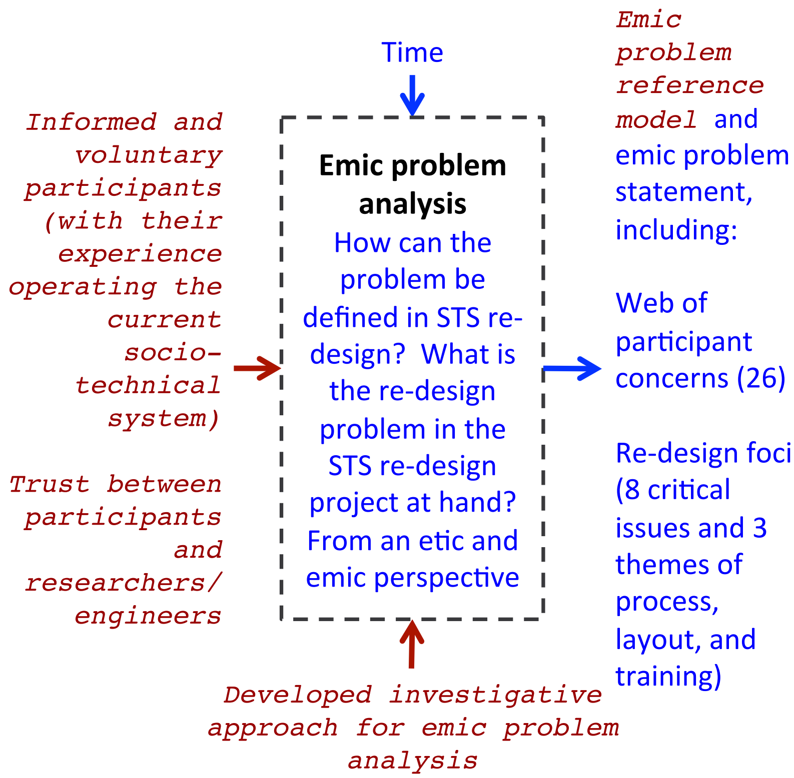


Figure 39: Emic problem analysis IDEF0

The position of "Emic problem analysis" (Figure 39) in this dissertation's model for re-designing a socio-technical system is shown in Figure 40.

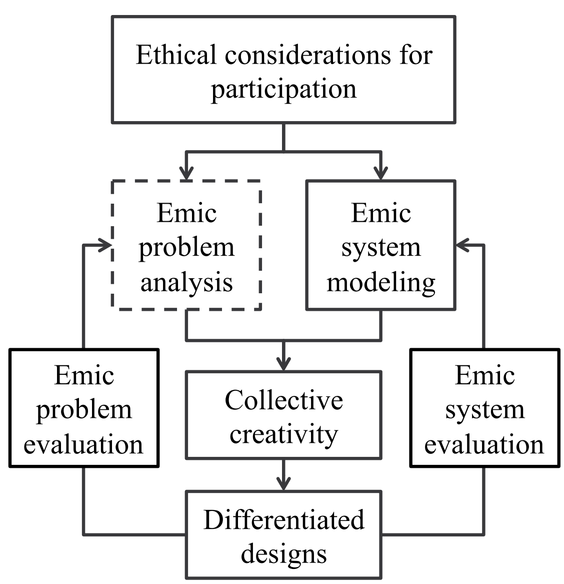


Figure 40: Emic problem analysis in the developed model for re-designing a socio-technical system

6 Emic system modeling in socio-technical system re-design

After establishing the ethical considerations for participation (Chapter 4), another next step in developing a participatory approach for re-designing a socio-technical system is to define a model of the socio-technical system. System studies are commonly positioned early in engineering design methodology (Pahl et al., 2007, p. 16) and systems design methodology (Whitten and Bentley, 2007, p. 30). Creating a system model makes the existing system design explicit, which is essential to re-designing a socio-technical system because it is a living system (e.g. system operators are within the system) and so its existing elements must be considered in re-design (as discussed in Chapter 1 and §6.1). The socio-technical system operators can provide critical insight on the existing design as participants, discussing (in interview) and showing (in observation) how they operate the system. What's needed is a way to model this participant information into a form that designers and participants can understand together, integrating the multi-perspective information into a whole to explicate the existing design and provide insight for re-design. Modeling the system also provides a basis for comparison, to measure any changes to the system before versus after a re-design intervention. Building a system model has not been explicitly related to STS theory in re-design (Table 5).

In turn, the research in this chapter asks: How can a socio-technical system be modeled from operator participation and how does it benefit re-design? What is the socio-technical system model in the re-design project at hand? This chapter investigates these questions with an emic (insider/participant) approach, grounding the research in qualitative methodology (§3.2) and further developing the descriptive study I of design research methodology (§3.1, Figure 6). The intention here is to explore this chapter's research questions *in situ* in the re-design of an assembly production system and socio-technical system archetype. The industrial context and participants are described in §3.4.

Consequently, this chapter sets out to develop an investigative approach for emic socio-technical system modeling in re-design, established in the modeling of the assembly production system in the re-design project. This developed investigative approach for emic system modeling (§6.2) analyzes field study data collection methods (interview and observation) with fuzzy cognitive mapping (FCM) techniques.

A cognitive map is a "qualitative model of how a system operates" (Özesmi and Özesmi, 2004, p. 44), consisting of causal relationships (linkages) between concepts (causes and effects). Cognitive maps have been used in political science (Axelrod, 1976) and have since been combined with fuzzy logic (Kosko, 1986) to create fuzzy cognitive maps. This modeling method is known for examining "people's perceptions of complex social systems" (Özesmi and Özesmi, 2004). As a "rapidly growing field" in knowledge engineering, FCM is advantageous in organizing big data and representing knowledge depth and connectivity (Papageorgiou, 2014). The ability to model people and systems with connectivity and depth makes fuzzy cognitive mapping suitable for modeling socio-technical systems. The FCM results (§6.3) and analysis (§6.4) are discussed in §6.5 and highlight that the emic investigative approach in §6.2 models the socio-technical system by identifying concepts and their inter-relationships that explain the system behaviour, principles, function, and structure as outlined in §6.1.

6.1 Relating a socio-technical system to the system design model

Since the intent of this research is to model the socio-technical system as a form that designers and participants can understand together, it's important to first define what is meant by a socio-technical system versus a technical system design model. The latter is the form of model that engineering designers are more likely to be familiar with, so it's important to identify the similarities and differences between it and a STS design model.

Zhang, Lin, and Sinha (2011) synthesize four regional schools of the engineering system design model (Australian, Japanese, American, and European). They provide a conceptual model of design as a technical system (what is designed), not to be confused with a process of design (the act of practicing design). The synthesized design model (Zhang, Lin, and Sinha, 2011; Lin and Zhang, 2004) is summarized as follows:

- A technical design consists of entities that are meaningfully connected and are perceived as states when the system is in operation;
- States exist in the physical domain (numerical or categorical), can be described by state variables, and relate to one another through constraints (internal and external). Internal constraints relate to the connection between

entities that form the system at time t; the external constraints are imposed from the environment to the entities in the system (p.3);

- The state reflects the system structure (different structures can lead to the same state);
- The independent state variable receives information, energy, and material from the outside environment into the system while the dependent variable offers them from the system to the outside environment;
- Context is a boundary that isolates the system from its environment;
- Behaviour is the response of the system when it receives stimuli – the relation between the independent (input) and dependent (output) state variables;
- A principle, or principles, govern the system behaviour; and
- Function can be described generally as the relation between the context and the behaviour, both generally and specifically.

These definitions and the overall model (Zhang, Lin, and Sinha, 2011; Lin and Zhang, 2004) are illustrated in Figure 41.

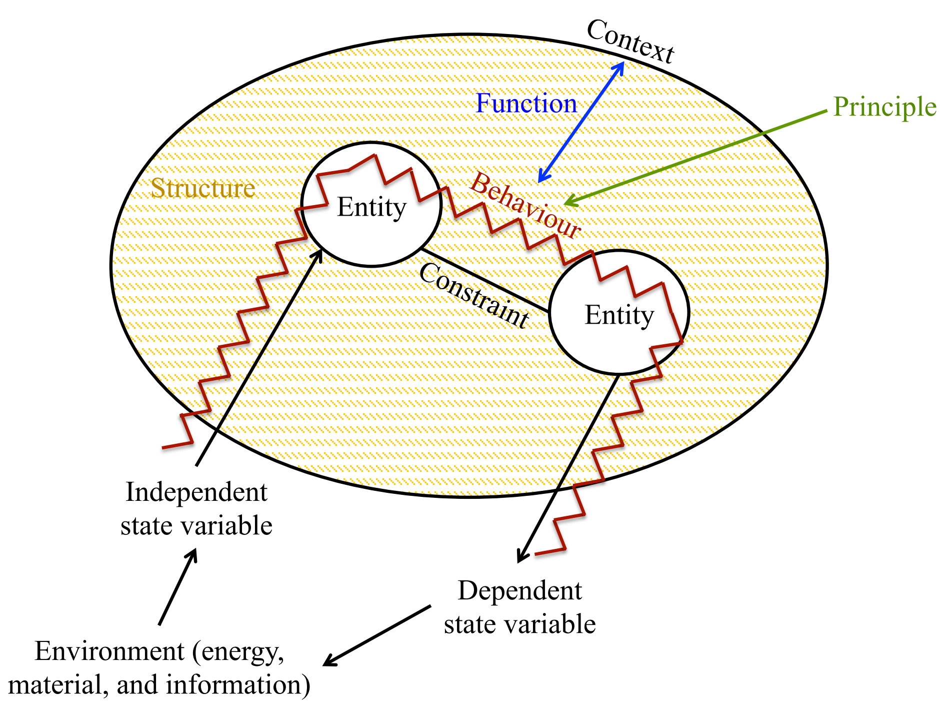


Figure 41: A technical system design model (after (Zhang, Lin, and Sinha, 2011))

Zhang, Lin, and Sinha's (2011) design model, Figure 41, defines a technical system in engineering design. It also helps to explain several definitions in engineering design upon which modeling techniques are built. For example, Pahl et al.'s (2007) definition for function is widely used in technical system design: a function is "derived for each task from the conversions of energy, material and signals" (p. 29). This definition clearly relates the environment to the independent state variable in Zhang, Lin, and Sinha's (2011) design model This definition for function is core to Pahl et al.'s (2007) functional modeling as a function structure (a block diagram), which defines subtasks (inputs and output relations) into subfunctions to fulfill the overall technical system function either directly (main subfunctions) or indirectly (auxiliary subfunctions). This definition's focus on energy, materials, and signals does not address the social and human value that is fundamental to socio-technical system theory, discussed in Chapter 2; so it is not appropriate to directly use this definition in STS re-design.

It is important to note that human aspects have been related to Pahl et al.'s (2007) function definition, but this does not make the relation socio-technical. For example, Hirtz et al. (2002) relate human aspects to Pahl et al.'s (2007) function definition in terms of energy conversion (providing human energy or force to a device); material flow (providing the human body to cross a device's boundary); and signal status (providing human senses in receiving device signals). In these relations, people provide an input to the technical device (a user). Conversely, in socio-technical systems people play an integral role in operating the system – people are *in* the system rather than peripheral to it (as discussed in Chapter 1). Consequently, an understanding of the socio-technical system design model is needed, in particular how it compares with the technical system design model in Figure 41, which requires relating socio-technical systems theory to Figure 41.

In STS theory, one of the most salient features of a socio-technical system is that workers operate the system, discussed in Chapter 1. This means that the socio-technical system operators are part of the entities positioned within the system context and are part of the system structure. The entities in a socio-technical system are therefore not just objects (as in a technical system) but are also human Subjects. In turn, the system behaves according to operations that transform inputs into outputs via human-object relations within the system. These operations are constrained in time by precedence (order of operations). The general context is the socio-technical system and the specific context here is the assembly production system. Accordingly, the specific inputs (independent state variables) include a description of the assembly parts and the specific outputs (dependent state variables) include a description of the final assemblies. These relations between the socio-technical system and Figure 41 are illustrated in Figure 42.

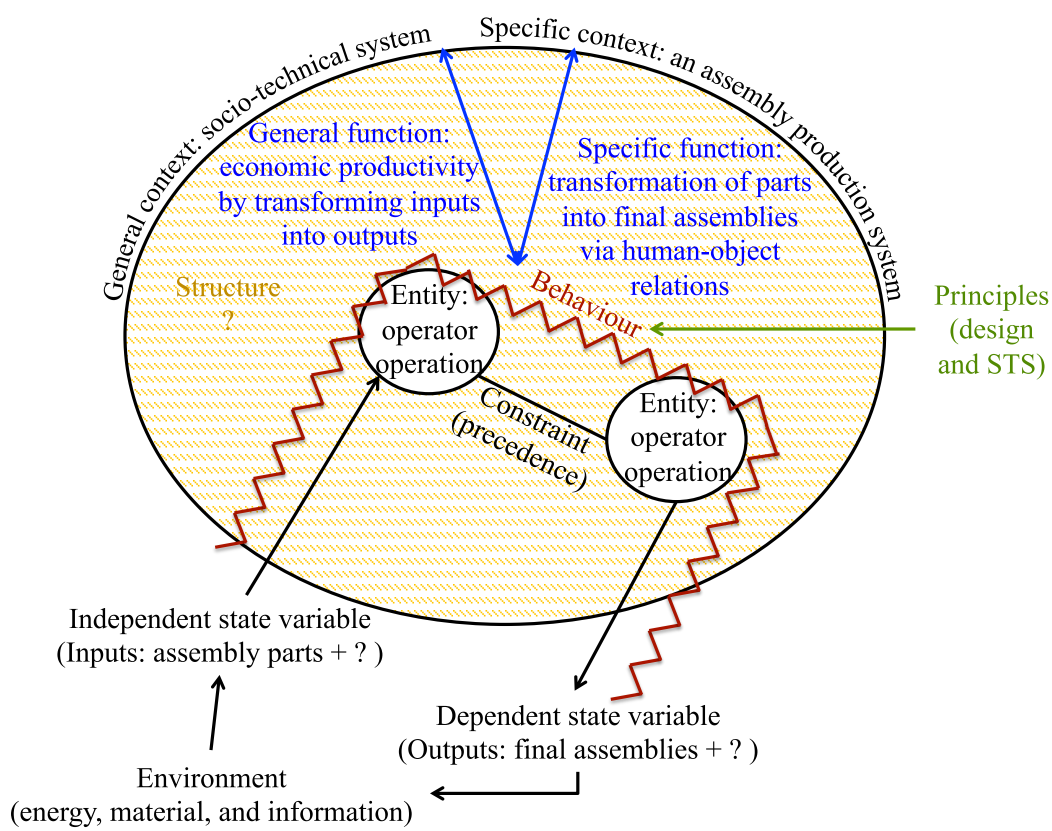


Figure 42: A STS design model in relation to Zhang, Lin, and Sinha's (2011) design model

Figure 42 also relates the prior definitions of the design model to a STS design model:

- A socio-technical design consists of human-object entities (operations) that are meaningfully connected (socio-technical) and are perceived as states when the system is in operation;

- The general function of the socio-technical system from the literature aligns and is defined as economic productivity (Emery, 1989b, p. 15) by acquiring inputs and transforming them into outputs (Pasmore, 1988, pp. 55-56); and
- The specific function of the assembly production system is to transform inputs (namely assembly parts) into outputs (namely final assemblies) via human-object relations (namely operator operations), providing precision to the general function through context.

These definitions are integral to the socio-technical system design model (Figure 42). This model also clarifies that modeling the socio-technical system in re-design is concerned with explicating the system behaviour (inputs, operations, constraints, outputs and their interrelationships); the principles that govern the system behaviour; the structure that the system behaviour reflects; and the function that relates the behaviour to the context.

Figure 42 also provides a reference point to differentiate between the socio-technical system concept and the use concept. In the socio-technical system concept, workers are entities within the system. In the use concept, users relate to the independent state variable – providing an input to the artefact/device/technical system. The two concepts are, however, not exclusive. For example, within the socio-technical system an operator can use a machine (a technical system that consists of inanimate objects) as a sub-system. Similarly, there can be social sub-systems within the socio-technical system (e.g. an organizational structure). The focus of this paper is on the human-object relations (integrated socio-technical aspects), which provides a more macro perspective than the object-object relations (technical system(s) within the STS) but not as broad as the inclusion of the human-human relations (social system(s) with the STS).

6.2 The emic STS modeling investigative approach

The investigative approach for emic socio-technical system modeling in re-design begins with data collection (§6.2.1) followed by fuzzy cognitive mapping data analysis (§6.2.2).

6.2.1 Data collection methods

Data is collected with field study. In design, field study "involves observation and interviewing" ("Field Study | Usability Body of Knowledge," 2012). In the research presented here, field study is a method for collecting data with participants (STS operators) about how they operate the assembly production system (a socio-technical system archetype) that involves observation and interviewing.

Observation and interview are useful research and design methods because they collect data from within the context of the socio-technical system, positioning the research in situ. The combination of the two methods also provides an inter-disciplinary perspective in keeping with the socio-technical system nature. Interview is a qualitative method common to the social sciences and captures the participants' knowledge of operating the STS. Observation can be both qualitative and quantitative, with quantitative measurement common to engineering, and it captures the participants' practice operating the STS. Since these methods involve participants (18 here in the roles of builder, planner, lead hand, supervisor, and manager), the ethical considerations for participation in STS re-design need to be operationalized first, establishing trust between the participants and researchers/engineers and a foundation for data reliability (as discussed in Chapter 4).

Semi-structured pre-interviews are conducted with participants, recorded, transcribed, and then verified. Here, 8 participants took part in the pre-interview in the roles of builder, lead hand, planner, supervisor, and manager (per the inclusion principle in Chapter 4). Four of the pre-interview questions are critical here: (1) How would you describe the current assembly process? (2) How would you describe your work with the current assembly process? (3) How would you describe an ideal assembly process? (4) How would you describe your ideal work with the ideal assembly process? The questions align with socio-technical system theory, since "Occupational roles express the relationship between a production process and the social organization of the group. In one direction, they are related to tasks, which are related to each other; in the other, to people, who are also related to each other" (Trist and Bamforth, 1951, p. 14). This principle also relates to the socio-technical system design model in Figure 42: work describes the object-human relation that is fundamental to the STS behaviour.

Pre-observations are conducted at random time intervals by observing the participants' operation of the assembly production system. Here, 10 unique data sets (production runs) of pre-observations were observed consisting of 226 unique data members (assembly cycles) in total. These data sets correspond to 10 different final assemblies and 4 different product platforms, with an average of 22 assembly cycles of each observed. The following data is collected for each production run via pre-observation and utilized here:

- Assembly process steps;
- Layout sketches including the relative location, size, orientation, position, and proximity of people and objects (e.g. table, skids, tools, etc.), as previously shown in Figure 9 and §3.4;
- Discrete or count data: production volume, number of components, number of different components, and pallet count;
- Categorical data: assembly code, final assembly (product) platform, and production phase; and
- Continuous data: cycle time (min/assembly).

This data informs an understanding of the socio-technical system function via system structure (e.g. layout), inputs (e.g. number of components), behaviour (e.g. process steps), and a direct measure of the function of the assembly production system (cycle time) – all relating back to the STS design model (Figure 42).

6.2.2 Fuzzy cognitive mapping (FCM)

After the interview and observation data is collected, it is analyzed and integrated using fuzzy cognitive mapping (FCM). The fuzzy cognitive mapping procedure is divided into (A) Data coding; then (B) Organizing the coding into an adjacency matrix and plotting the adjacency matrix to create a fuzzy cognitive map; and finally (C) Analyzing the plot and adjacency matrix. This procedure is explained here and demonstrated in Appendix O.

(A) The FCM data coding is performed as follows. In the FCM literature, data can be coded from questionnaires (Roberts, 1976), by participants in an interview (Carley and Palmquist, 1992), from interview texts (Wrightson, 1976) or through data (Schneider et al., 1998). The last two methods are utilized in this paper. The interview text coding technique is used to inquire into operator/participant knowledge (§6.2.2.1). An adaptation of the data coding technique is used to code observations to inquire into operator/participant practice (§6.2.2.2). The coding results in identifying relationships in the form of cause concept/linkage/effect concept (or Subject/verb/object). A 'cause' is defined here as a concept that precedes or leads to the effect concept. Correspondingly, the 'effect' is a concept that proceeds from or follows the cause concept. The coding is made "fuzzy" by giving the linkage a fuzzy value between -1 and 1, making fuzzy cognitive maps both qualitative and quantitative in nature. After the FCM data is coded, it can then be visualized and analyzed.

(B) Organizing the coding into an adjacency matrix and plotting the adjacency matrix to create a fuzzy cognitive map is performed as follows. The FCM coding is transferred into an adjacency matrix composed of causes (rows), effects (columns), and corresponding linkage values. This adjacency matrix is then plotted as a di-graph with cause and effect concepts (nodes) and linkages (arrows or vectors). This process is further described in §6.2.2.3. The di-graph is called the fuzzy cognitive map. A simple version of a fuzzy cognitive map is shown in Figure 43 on the left.

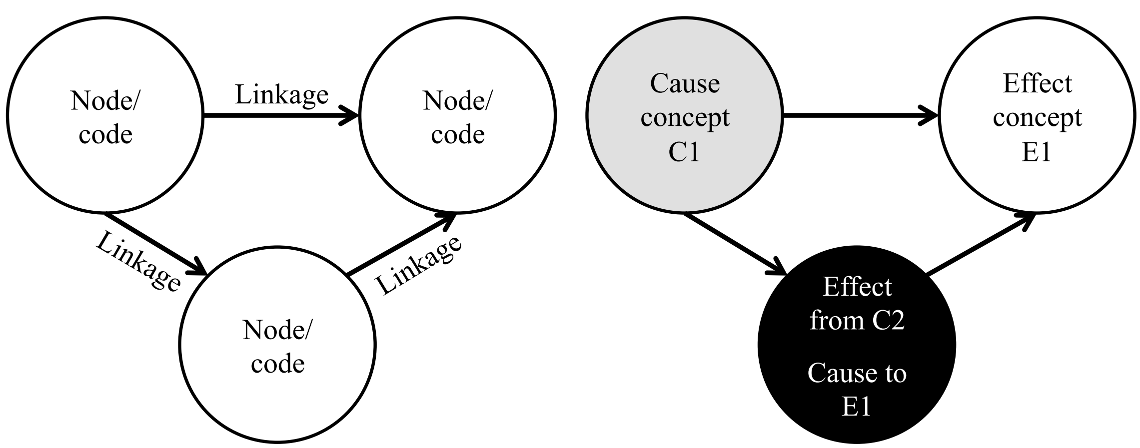


Figure 43: Simple fuzzy cognitive map

(C) The FCM plot and adjacency matrix is analyzed as follows. Each node in the matrix and plot is analyzed for how many linkages enter or exit it. Nodes are categorized as a transmitter (overall cause concept); receiver (overall effect concept); or ordinary variable (a cause and effect concept). This process is further described in §6.2.2.4. The nodes from Figure 43 (left) are analyzed and shaded as transmitter (grey), receiver (white), or ordinary variables (black) in Figure 43 on the right.

The fuzzy cognitive mapping procedure models the socio-technical system from coding data that describes the socio-technical system in situ (as discussed in §6.2.1) and identifies the concepts and their inter-relationships that explain the system behaviour (inputs, operations, constraints, and outputs); the principles that govern the system behaviour; the structure that the system behaviour reflects; and the function that relates the behaviour to the context (per Figure 42).

6.2.2.1 FCM coding from interview

Each interview transcript is coded using Wrightson's (1976) FCM coding techniques, which analyze the text both structurally and by content. In general, the coding process outlined by Wrightson (1976) is summarized below and applied here to decompose the interview text into coding, one interview at a time:

1. Is there a relationship? In English grammar, the simplest structure for identifying a relationship in the interview text is: Subject-Verb-Object. This translates into FCM terminology as: cause concept-linkage-effect concept. The interview text is read and the relationships are identified. Each relationship is further coded with steps 2 – 4, one relationship at a time.
2. What is/are the concept(s) in the identified relationship? A concept must be able to take on a value. For example, the term "the process" is not a concept because "the process" does not have a value. The term, "the efficiency of the process" is a concept because efficiency can have a value. Concepts can also be events, where the value is in terms of it occurring or not. Concepts are isolated in the identified relationships.

3. Identify the cause concept and the effect concept (in the isolated concepts in the identified relationship). There are many special cases (e.g. complex cause, complex effect, etc.) that Wrightson (1976) outlines in detail. In general, the following questions are helpful to ask when identifying concepts as either cause or effect:
   a. Does the concept initiate the action (cause concept)?
   b. Does the concept receive the action (effect concept)?
4. What is the link symbol and its (fuzzy) logic value between the cause concept(s) and the effect concept(s) (in the isolated concepts in the identified relationship)? Wrightson (1976) outlines in detail several special cases. In simplest form, the linkages in Table 17 exist. The linkage is coded with a symbol and then a value.

Link symbol	Link value	Link meaning (associated verbs)
+	1	Positively associated with e.g. by, would, is based on, would be more, want to
-	-1	Negatively associated with e.g. eliminate, don't have to, no need for, does not require
⊕	0.5	Will not hurt, does not prevent, is not harmful to
⃠	-0.5	Will not help, does not promote, is of no benefit to
a	0	May or may not be related to, affects indeterminately

Table 17: Fuzzy cognitive map linkage values and meanings (linkages based on Wrightson (1976) and fuzzy logic values based on (Kosko 1986))

In conjunction with the preceding coding process, the following coding guidelines from Wrightson (1976) are also particularly useful:

- Focus on denotation, not interpretation;
- Avoid paraphrasing as much as possible;
- Replace general pronouns (e.g. it, they, we) with specific nouns;
- Record future statements in present tense (e.g. "usually what you'd like to do");
- "By," "from," and "because of" precede cause concepts (create structural reversals in sentence structure);

- Chain of events assertions (A then B then C) create the relationships A→B and B→C (so B becomes both a cause and an effect);
- If/then is a cause-effect relationship; and
- Pay special consideration to interdependence. In general, there is no interdependence coded in effects (e.g. if A causes B and C, then A→B and A→C). However, if (B and C) is an interdependent cause that affects D, then these concepts are coded together (e.g. (B and C)→ D).

One exception to Wrightson's (1976) coding guidelines is made here. While Wrightson (1976) cautiously states that implied linkages may be mapped, in this research it is avoided as much as possible. In doing so, here it is found that while a linkage may have been implied in one interview, another interview stated the linkage explicitly and in doing so effectively represented the relationship.

Each pre-interview transcript is coded individually using the preceding coding steps. In the pre-interview here, 26 relationships (cause/link/effect) were coded on average per transcript. After this initial coding has been completed, similarities between concepts are evaluated in a merging process to ensure that the resulting codes are unique and similar codes are merged. Wrightson (1976) provides the following guidelines for code merging, emphasizing both content and context analysis:

- Mergers of concepts are more common when the document is broad in scope; if the text is highly specific, mergers are less common.
- Does the speaker make a distinction between the two things? If so, keep the concepts separate. If not, merge the concepts.
- Would the speaker believe that the logic had been distorted if the concepts were merged? If so, keep the concepts separate. If not, merge the concepts.
- Are antonyms used? E.g. A/-/ B is the same as –A + B which is the same as A /+/ -B

After the merging process is applied to the codes in each pre-interview, the merging process is then applied across the codes in all of the pre-interviews. The coder must pay careful attention to ensure that the concepts being merged are indeed similar enough to warrant the merger. In this case, the original texts are re-read, sometimes multiple times, to assess the context in which the relationship is given. Once a list of all the codes has been made, they are numbered so that the same concept mentioned in multiple interviews has the same code.

Via this coding process, the participant's knowledge of his/her operation of the socio-technical system shared in interview is coded as concepts (cause or effect) and linkages. This individual knowledge is connected to the other participants' knowledge by the merged coding. This is in line with the principles of grounded theory and the emic (or insider) perspective of capturing participant/operator insights on the STS.

6.2.2.2 FCM coding from observation

Before the pre-observation data can be coded, it is synthesized into an operational model representing the data gathered in §6.2.1. This operational model and the process for building it are outlined in (Townsend and Urbanic, 2015) and Chapter 9 where it is used to compare pre- and post-observations. For the purpose of this chapter and fuzzy cognitive mapping, the operational model is composed of Equation 5 to Equation 11 from (Townsend and Urbanic, 2015), where Equation 5 is formatted per Figure 90 and the highest R-sq correlation between r_i and mean cycle time for the pre-observation data.

$$r_i = V_i + PC_i + |DR_i| + |TR_i| + |PR_i| + |AR_i| \qquad \text{Equation 5}$$

$$V_i = 1 - \frac{n_i}{2Vol_{max}} \qquad \text{Equation 6}$$

$$V_i = \frac{n_i}{2Vol_{max}} \qquad \text{Equation 7}$$

$$|DR_i| = \frac{|DA_i - DB_i|}{DT_i} \qquad \text{Equation 8}$$

$$|TR_i| = \frac{|TA_i - TB_i|}{TT_i} \qquad \text{Equation 9}$$

$$|PR_i| = \frac{|PA_i - PB_i|}{PT_i} \qquad \text{Equation 10}$$

$$|AR_i| = \frac{|AA_i - AB_i|}{AT_i}$$ Equation 11

The nomenclature for Equation 5 to Equation 11:

i	Given production run, where i=1, 2, … 10 in the pre-observations
n_i	Number of observation samples in i (i.e. the number of assembly cycles, or number of final assemblies built, observed in the production run)
V	Production phase factor (Equation 6 for the observations taken from the beginning of the production run; Equation 7 for the observations taken from the end or the full production run)
PC	Pallet count, which accounts for the overall size of the final assembly
DR	Distribution of work ratio related to the number of different components
DA	Number of different components that builder A handles
DB	Number of different components that builder B handles
DT	Number of different components in the final product assembly (DA + DB)
TR	Distribution of work ratio related to the total number of components
TA	Number of total components that builder A handles
TB	Number of total components that builder B handles
TT	Number of total components in the final product assembly (TA + TB)
PR	Distribution of work ratio related to the number of picking tasks
PA	Number of picking tasks that builder A performs
PB	Number of picking tasks that builder B performs
PT	Number of picking tasks for the final product assembly (PA + PB)
AR	Distribution of work ratio related to the number of assembling tasks
AA	Number of assembling tasks that builder A performs
AB	Number of assembling tasks that builder B performs
AT	Number of assembling tasks for the final product assembly (AA + AB)
r	Complexity value

In the nomenclature, a “picking task” refers to selecting the components. An “assembling task” refers to the combining and positioning of the selected assembly components. With this nomenclature and the operational model equations, Equation 5 to

Equation 11, the observation FCM is derived via the following steps. These steps are organized in the same sequence as the steps to derive a FCM from text.

1. Is there a relationship? In the operational model, a relationship is identified by an = sign. This translates into FCM terminology as: cause concept-linkage-effect concept. Relationships are identified, and each equation is further coded with steps 2 – 4, one equation at a time.
2. What is/are the concept(s) in the identified relationship? A concept must be able to take on a value. Variables in the equation can be a concept; however, the variables may be interdependent. If this is the case, the interdependence is mapped as one concept, e.g. $|TA_i\text{-}TB_i|$ has a separate meaning from TA or TB individually; therefore, it is considered as one concept. Constants are integrated into the concept. Concepts are isolated in the identified relationship.
3. Identify the cause concept and the effect concept (in the isolated concepts in the identified relationship). This is evaluated in the context that the equation refers to, e.g. $|TR| = |TA_i\text{-}TB_i| / (TA_i + TB_i)$. In this equation, the two concepts on the right side of the equation (the numerator and the denominator) can be directly measured from the layout sketch. The variables then combine via the operators to inform TR; TR has no meaning without the prior concepts on the right hand side of the equation being defined. Therefore, TR is the effect, and the two concepts on the right side of the equation are two separate causes. It may help to consider the concepts as inputs (causes) and outputs (effects).
4. What is the link and its (fuzzy) logic value between the cause concept(s) and the effect concept(s)? The linkage is coded with a symbol and a value as follows. The following mathematical operations can be understood as links with symbols and values as follows.

When / or * operators are used (and the concepts in the equation are not interdependent), then the other concepts in the equation can be substituted with the value of 1 and the relationship then compared, where = or * is a positive relationship that is directly proportional (+1) and / is a negative relationship that is inversely proportional (-1). This is illustrated in the following Equation 9, previously shown, which is coded as follows:

$$|TR_i| = \frac{|TA_i - TB_i|}{TT_i} \qquad \text{Equation 9}$$

TT	/+1/	$TA_i + TB_i$
$TA_i + TB_i$	/-1/	$\mid TR_i \mid$
$\mid TA_i - TB_i \mid$	/+1/	$\mid TR_i \mid$

Note: TR has no meaning until the other terms in the equation define it; therefore it is the effect and the equation cannot be rearranged. Also, TT is the total number of components that are then divided between builder A and B; therefore TT is the cause concept and ($TA_i + TB_i$) is the effect concept.

When + or – operators are used in an equation (and the concepts in the equation are not interdependent), then the concepts in the equation can be substituted with the value of 1 and the relationship then compared, where + is a positive relationship (+1) and – is a negative relationship (-1). This is illustrated in Equation 5, previously shown, which is coded as follows:

$$r_i = V_i + PC_i + |DR_i| + |TR_i| + |PR_i| + |AR_i| \qquad \text{Equation 5}$$

V_i	/+1/	r
PC_i	/+1/	r
$\mid DR_i \mid$	/+1/	r
$\mid TR_i \mid$	/+1/	r
$\mid PR_i \mid$	/+1/	r
$\mid AR_i \mid$	/+1/	r

Note: r has no meaning until the other six terms in the equation define it; therefore it is the effect and the equation cannot be rearranged.

In the observation operational model (Townsend and Urbanic, 2015), the relation between r_i and mean cycle time (X-barCT_i) is shown to be linear, e.g. X-barCT_i = $1.2099r_i + 1.0333$. This is further explained in Chapter 9, Figure 90. These equations comprise the observation operational model and are coded for the purposes of fuzzy cognitive mapping in this chapter. Via this coding process, the participants' practice of operating the socio-technical system shared in observation is coded as concepts (cause or effect) and linkages. This is in line with the principles of grounded theory and the emic (or insider) perspective of capturing participant/operator insights on the STS.

6.2.2.3 FCM adjacency matrices and plots

The coding from each interview is translated into a square adjacency matrix (A) for each interview ($A_{interview}$). The number of concepts in each interview determines the size of the square adjacency matrix (A_{ij}) for each interview. The cause concepts are represented as rows (i) in the adjacency matrix and the effect concepts are represented as columns (j). Each linkage fuzzy logic value is placed in the adjacency matrix (a_{ij}) according to its cause concept (row) and effect concept (column). This process forms an adjacency matrix for each interview ($A_{interview}$) that represents individual participant (socio-technical system operator) knowledge. Since there are eight interviews in this study, there are eight $A_{interview}$ matrices.

In order to see the interviews as a whole – as collective knowledge across all of the participants (socio-technical system operators) – the $A_{interview}$ matrices are integrated into a collective interview adjacency matrix ($A_{interviews(all)}$). Since one interview can contain the same concept that's expressed in another interview, they are integrated (rather than summed) interview-to-interview. The integration process starts with the first interview adjacency matrix ($A_{interview1}$). Concepts in $A_{interview2}$ that differ from $A_{interview1}$ are added as rows and columns to $A_{interview1}$ to form $A_{interview1\text{-}2}$. Linkage values from $A_{interview1}$ remain and linkage values from $A_{interview2}$ are placed in their corresponding locations in $A_{interview1\text{-}2}$. Redundant linkage values are compared (not added). This checks for consistency in the coding process and across participant data; if there are any discrepancies, the interview transcripts are reviewed to see if there has been a coding error or to analyze the participant data. In this study, interview1 is integrated with interview2 into $A_{interview1-2}$, which is then integrated with interview3 into $A_{interview1-3}$, and so on until $A_{interview1-8}$ (which is $A_{interview(all)}$).

The coding from the observation (operational model) is translated into an adjacency matrix for the observation ($A_{observation}$) using the process outlined for each interview above. The $A_{observation}$ matrix represents the collective practice of the participants (socio-technical system operators). In order to see the interviews and observation as a whole – as the integrated knowledge and practice of the participants (socio-technical system operators) – the $A_{observation}$ and $A_{interview(all)}$ matrices are integrated into $A_{interviews(all)\&observation}$ by identifying common concepts and defining linkages.

The various matrices are plotted using social network visualization software to create the related fuzzy cognitive map. Each concept is considered a node or variable. Each linkage is plotted as a vector to indicate a cause and effect relationship. The vector direction follows from the cause to the effect. In this research, a negative vector is defined with a red dashed line; a positive vector is defined with a black solid line. Nodes are defined as ellipses with diameters relative to their centrality value, per Equation 14.

6.2.2.4 FCM analysis of the adjacency matrices and plots

The fuzzy cognitive plot (or map) can be analyzed in terms of its structure by examining the nature of each node and its relationship to other nodes via the adjacency matrix. The nodes can be understood as: transmitter variables, receiver variables, or ordinary variables. The variable type is based on calculations for in-degree (id) and out-degree (od), where in and out refer to the direction of the linkage vector(s) relative to the node. If the node only has an in-degree (od=0), the variable is an overall effect (receiver variable). If the node only has an out-degree (id=0), the variable is an overall cause (transmitter variable). If the node has both in-degree and out-degree (id≠0 and od≠0), it is an ordinary variable that plays an overall transitory role as both a cause and an effect relative to different nodes. In other words, the ordinary variables provide a means between the overall causes and effects.

The out-degree (od) for each variable is calculated in Equation 12 (Özesmi and Özesmi, 2004, p. 51) by the row sum of absolute values in the adjacency matrix. The out-degree corresponds to the cumulative, absolute value of linkages exiting the variable (v_i) across all of the variables in the map (N).

$$od(v_i) = \sum_{k=1}^{N} | a_{ik} | \qquad \text{Equation 12}$$

The in-degree (id) for each variable is calculated in Equation 13 (Özesmi and Özesmi, 2004, p. 51) by the column sum of absolute values in the adjacency matrix. The in-degree corresponds to the cumulative, absolute value of linkages entering the variable (v_i) across all of the variables in the map (N).

$$id(v_i) = \sum_{k=1}^{N} | a_{ki} | \qquad \text{Equation 13}$$

The centrality (c) for each variable is calculated in Equation 14 (Özesmi and Özesmi, 2004, p. 51) by the summation of the in-degree and out-degree.

$$c(v_i) = od(v_i) + id(v_i) \qquad \text{Equation 14}$$

There have been suggestions to analyze the complexity of a FCM plot based on the total number of receiver variables (Eden et al., 1992) or a receiver to transmitter ratio (Özesmi and Özesmi, 2004). Other considerations include the number of variables (N) in a FCM plot and the number of linkages (L, cf. Equation 15 after (Özesmi and Özesmi, 2004)).

$$L = \sum_{i=1}^{N} \sum_{j=1}^{N} | a_{ij}| \qquad \text{Equation 15}$$

After calculating these factors, the interconnectivity of a FCM plot can be calculated through its density (D, cf. Equation 16 (Özesmi and Özesmi, 2004, p. 51)). When each node is linked once to every other node with no self-loops, D = 1, indicating a high degree of interconnectivity.

$$D = \frac{L}{N(N-1)}$$ Equation 16

Another way of viewing complexity relative to a fuzzy cognitive map, not found in the current literature, is to consider the ordinary variables. Take for instance a FCM plot that is represented as a sphere in 3D space. The ordinary variables characterize the middle of the sphere, through which the overall causes and effects must travel through. In doing so, this also sets off a chain reaction amongst the ordinary nodes.

The emic system modeling investigative approach (§6.2) – data collection (§6.2.1) followed by FCM data analysis (§6.2.2) – is summarized in Figure 44.

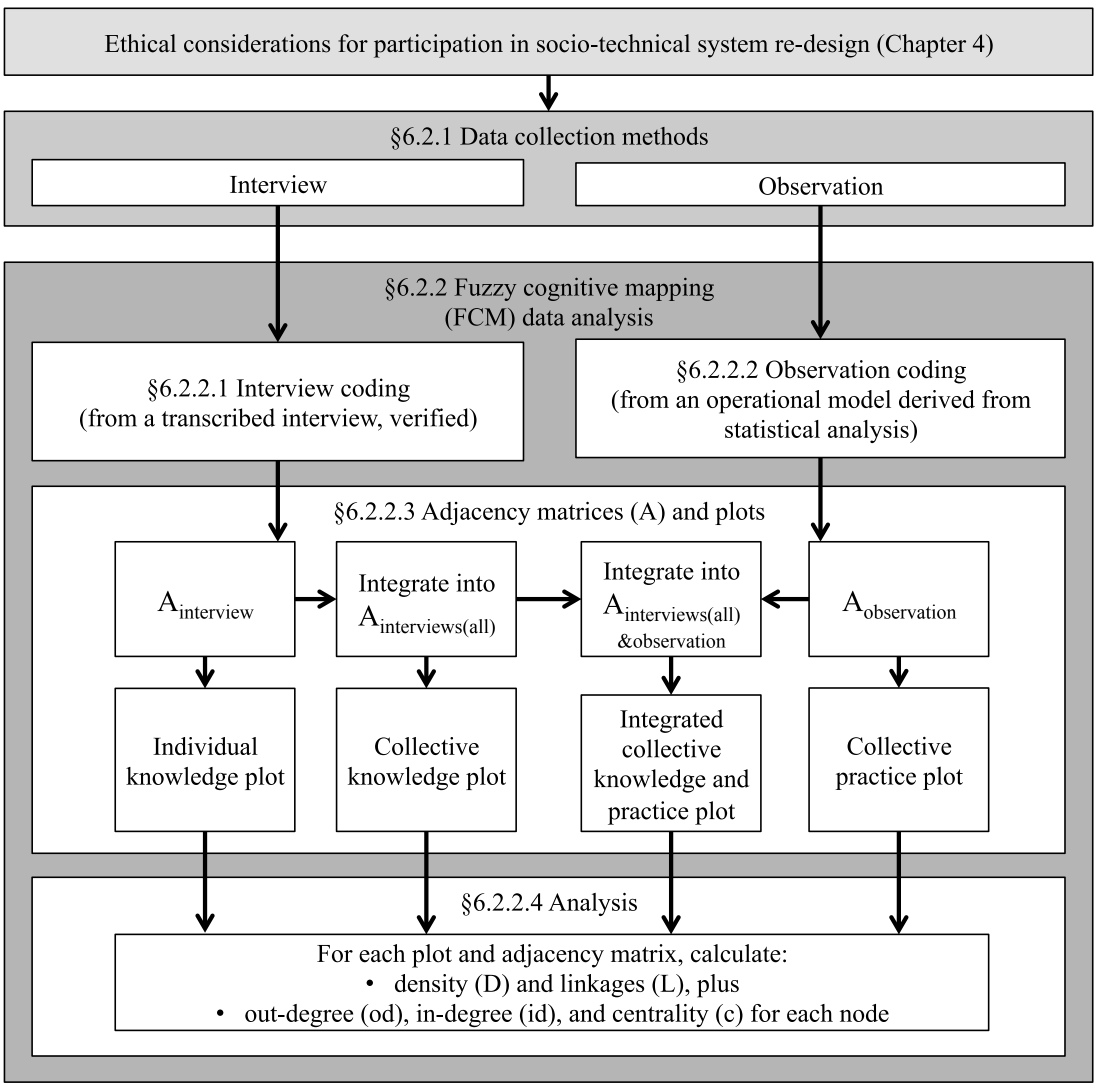


Figure 44: The emic system modeling investigative approach

6.3 Results

The results for the emic system modeling investigative approach in Figure 44 are aligned as follows. The results for the interview coding (§6.2.2.1) and associated adjacency matrices and plots (§6.2.2.3) are found in §6.3.1. The results for the observation coding (§6.2.2.2) and associated adjacency matrices and plots (§6.2.2.3) are found in §6.3.2. The results for the integrated interview and observation (§6.2.2.3) are found in §6.3.3. The analysis (§6.2.2.4) results are found in §6.4.

6.3.1 FCM from interviews

Interviews are coded individually, then each interview's codes are merged. Finally, the codes across all of the interviews are merged. In this study, this resulted in 120 different codes numbered 1-120. As mentioned in the merging guidelines by Wrightson (1976), "If a document is broad in scope, it follows that mergers of concepts are more likely to be appropriate than if the text is highly specific" (p.323). In the pre-interviews the text is very specific, which is understandable in an assembly production system where work is specialized and the participant pool represents a range of roles.

The coding results of two interviews, interview5 and interview7, are presented here. The interview order has been randomized for de-identification, meaning that interview5 was not necessarily the fifth interview conducted. Table 18 demonstrates a sample of the interview5 coding. For each of the two interviews, their adjacency matrices (Figure 45 and Figure 47) and corresponding FCM plots (Figure 46 and Figure 48) are shown. Negative values in the matrix cells are highlighted in red; positive values are highlighted in green.

Cause concept	Linkage	Effect concept
Different amount of components	-1	Having a designated take-up area (around the table)
Small work area	-1	Ability to maneuver skids
Variety of things being built	-1	Having a designated position (around the table)
No designated position	-1	Knowing where to put components in terms of staging
Assemblies are complete	+1	Builders pull out finished pallets and stage on floor
Builders pull out finished pallets and stage on floor	+1	Material handlers pick up the finished pallet
Material handlers pick up the finished pallet	+1	Immediately wrap pallet
Immediately wrap pallet	+1	Weigh pallet
Weigh pallet	+1	Put pallet up in the warehouse

Table 18: Sample of FCM coding (in interview 5)

Code	40	16	41	7	42	43	44	45	46	47	48	49	50	51	52	53	54	55	56	57	58	59	60	15	13	61
40	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
16	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
41	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
7	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
42	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
43	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
44	0	0	0	0	0	0	0	-1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
45	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
46	0	0	0	0	0	0	0	0	0	-1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
47	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
48	0	0	0	0	0	0	0	-1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
49	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0
50	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0
51	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	-1	0	0	0	0	0	0	0	0
52	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0
53	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0
54	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0
55	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
56	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0
57	0	0	0	0	0	0	0	0	0	0	0	0	0	-1	0	0	0	0	0	0	0	0	0	0	0	0
58	0	0	0	0	0	0	0	0	0	0	0	0	0	-1	0	0	0	0	0	0	0	0	0	0	0	0
59	1	0	0	0	0	0	0	0	0	0	0	0	0	-1	0	0	0	0	0	0	0	0	0	0	0	0
60	0	0	0	0	0	0	0	0	0	0	0	0	0	-1	0	0	0	0	0	0	0	0	0	0	0	0
15	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	-1	0
13	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
61	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0

Figure 45: Adjacency matrix for interview5 ($A_{interview5}$)

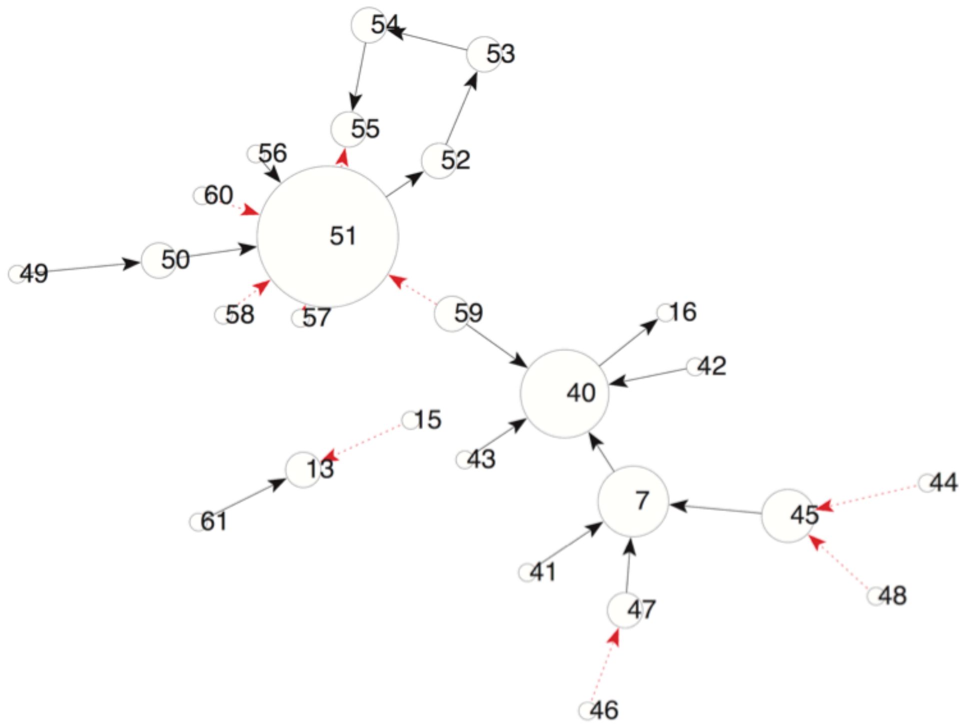


Figure 46: FCM plot for interview5 (from $A_{interview5}$)

Code	63	16	71	66	64	5	17	31	33	68	67	74	75	76	77	78	79	80	81	82	83	84	85	86	87	88	89	90	91
63	0	1	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
16	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
71	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
66	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
64	0	0	0	1	0	0	0	0	0	0	-1	0	0	0	0	-1	0	0	0	0	0	0	0	0	0	0	0	0	0
5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
17	0	0	0	0	0	0	0	-1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
31	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
33	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
68	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	-1	0	0	1
67	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
74	0	0	0	0	0	0	0	0	0	0	0	0	-1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
75	0	0	0	0	0	0	0	0	0	0	0	0	0	-1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
76	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
77	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
78	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
79	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0
80	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	-1	0	0	0	0	0	0	0	0	0	0
81	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
82	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0
83	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
84	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	0	0	0	0	0
85	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
86	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
87	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	-1	0
88	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
89	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	-1	0	0	0	0
90	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
91	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

Figure 47: Adjacency matrix for interview7 ($A_{interview7}$)

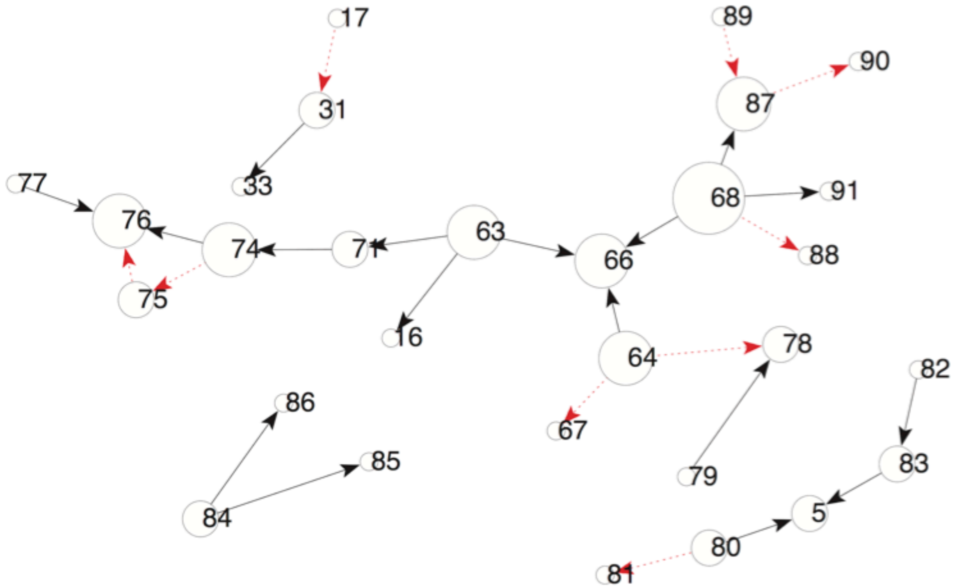


Figure 48: FCM plot for interview7 (from $A_{interview7}$)

The adjacency matrix for each interview is integrated into a collective interview adjacency matrix ($A_{interview(all)}$) that represents the participants' collective body of knowledge about the assembly production system operation and utilizes the merged coding system (1-120). The collective interview adjacency matrix ($A_{interview(all)}$) is formed interview-to-interview, using the process described in §6.2.2.3. The following Figure 49 represents a fuzzy cognitive map of the adjacency matrix that integrates interview1, 2, and 3 ($A_{interview1-3}$), which illustrates three trees (to refer to graph theory).

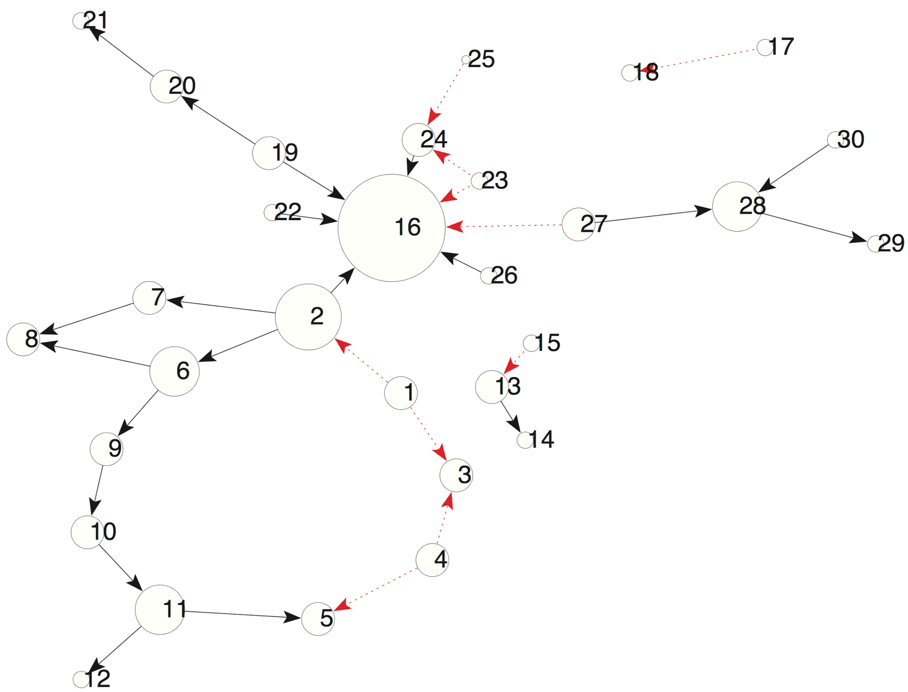


Figure 49: FCM plot for integrated interviews 1, 2, and 3 (from $A_{interview1\text{-}3}$)

The process of integrating from interview-to-interview and the resulting number of trees in the integrated plot is outlined in Table 19. The number of nodes (N) in the FCM plot is also shown, along with the number of nodes in each tree of the plot, which informs the % cohesion (the number of concepts in the map that are incorporated into the main tree).

Integrated interviews	# of nodes (N) in FCM plot	# of trees in FCM plot	# of nodes in primary tree (T1)	# of nodes in secondary tree (T2)	# of nodes in tertiary tree (T3)	# of nodes in quaternary tree (T4)	% cohesion (T1/N)	Plot in 2D or 3D
$A_{interview1\text{-}2}$	22	3	17	2	3	0	77.3%	2D
$A_{interview1\text{-}3}$	30	3	25	2	3	0	83.3%	2D
$A_{interview1\text{-}4}$	39	2	36		3	0	92.3%	2D
$A_{interview1\text{-}5}$	61	2	57		4	0	93.4%	2D
$A_{interview1\text{-}6}$	73	2	69		4	0	94.5%	2D
$A_{interview1\text{-}7}$	91	3	84		4	3	92.3%	2D
$A_{interview1\text{-}8}$ $A_{interview(all)}$	120	1	120				100%	3D

Table 19: Integrated interviews and FCM plot overview

When the codes from interviews 1-8 are merged (from 247 codes before merging to N=120) and the adjacency matrices are integrated interview-to-interview, a collective group interview adjacency matrix is formed ($A_{interview(all)}$) and plotted; one interconnected tree emerges. This indicates that multiple participants, from multiple operator perspectives, express the big picture of the socio-technical system. This is also representative of the qualitative theory of saturation – an indicator of sufficient participation in terms of answering the research question. As shown in Table 19, as more interviews (participants) are involved, the % cohesion typically increases (5 out of 6 times), although it may also bring new concepts unrelated to the main tree, as in the integrated interviews 1-7 compared with integrated interviews 1-6. This is why the inclusion principle is critical in assessing the participant pool. The collective interview FCM plot is 3D and shown in 2D in Figure 50.

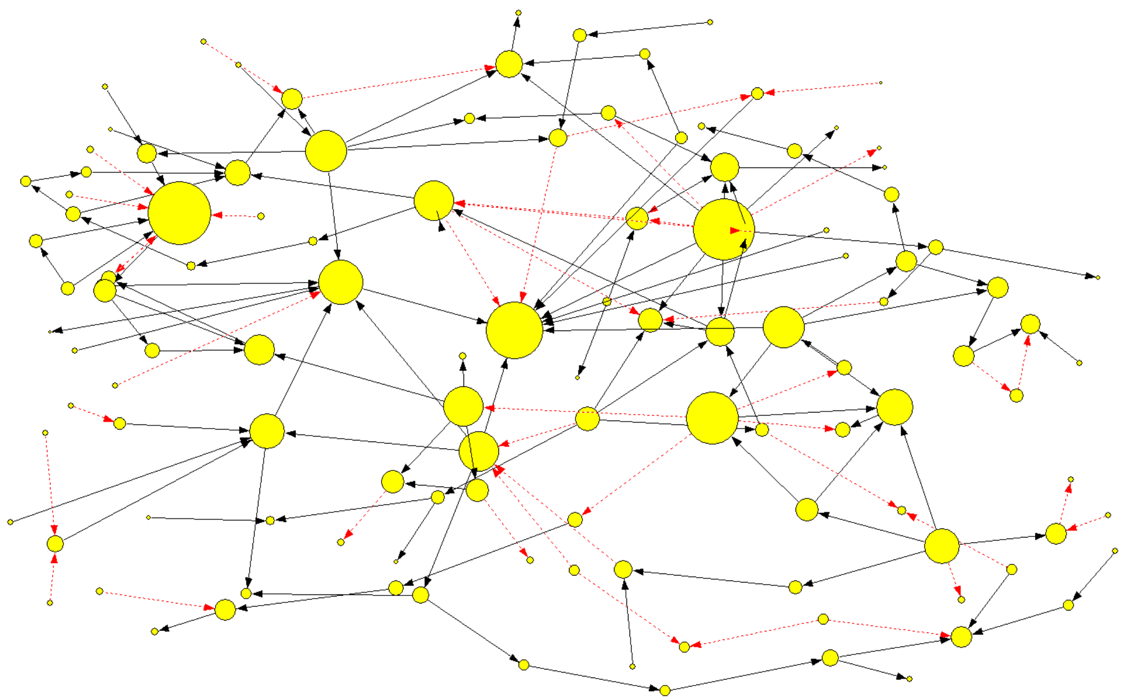


Figure 50: FCM plot of the collective interview

6.3.2 *FCM from observations*

The observation (operational model) is coded using Equation 5 to Equation 11. Since ri (Equation 5) is a sum of variables with their own equations, those constituent variables are coded first. Vi is coded from Equation 6 and Equation 7. An additional 'S' variable is added to represent the concept "start of production run," which affects the production phase variable (Vi). DRi is coded from Equation 8. TRi is coded from Equation 9. PRi is coded from Equation 10. ARi is coded from Equation 11. Then ri is coded from Equation 5. The coding results of one equation, Equation 8, is presented in Table 20:

Cause concept	Link	Effect concept
Number of different components in the final product assembly (DT_i)	+1	Number of different components that builder A and B handle ($DA_i + DB_i$)
Number of different components that builder A and B handle ($DA_i + DB_i$)	-1	Distribution of work ratio related to the number of different components $\lvert DR_i \rvert$
Difference between the number of different components that builder A and B handle $\lvert DA_i - DB_i \rvert$	+1	Distribution of work ratio related to the number of different components $\lvert DR_i \rvert$

Table 20: Cause concepts, effect concepts, and linkages for DR variable for the observation

From this coding, the adjacency matrix in Figure 51 is created, with positive values in green and negative values in red. From this adjacency matrix of the observation ($A_{observation}$), the following FCM plot in Figure 52 is drawn.

<table>
<tr><th>Code</th><th>TT</th><th>TA+TB</th><th>|TA-TB|</th><th>|TR|</th><th>DT</th><th>DA+DB</th><th>|DA-DB|</th><th>|DR|</th><th>PT</th><th>PA+PB</th><th>|PA-PB|</th><th>|PR|</th><th>AT</th><th>AA+AB</th><th>|AA-AB|</th><th>|AR|</th><th>n/2Volmax</th><th>1-(n/2Volmax)</th><th>V</th><th>S</th><th>PC</th><th>r</th><th>Mean Cycle Time</th></tr>
<tr><td>TT</td><td>0</td><td>1</td><td>0</td><td>0</td><td>0</td><td>0</td><td>0</td><td>0</td><td>0</td><td>0</td><td>0</td><td>0</td><td>0</td><td>0</td><td>0</td><td>0</td><td>0</td><td>0</td><td>0</td><td>0</td><td>0</td><td>0</td><td>0</td></tr>
<tr><td>TA+TB</td><td>0</td><td>0</td><td>0</td><td>-1</td><td>0</td><td>0</td><td>0</td><td>0</td><td>0</td><td>0</td><td>0</td><td>0</td><td>0</td><td>0</td><td>0</td><td>0</td><td>0</td><td>0</td><td>0</td><td>0</td><td>0</td><td>0</td><td>0</td></tr>
<tr><td>|TA-TB|</td><td>0</td><td>0</td><td>0</td><td>1</td><td>0</td><td>0</td><td>0</td><td>0</td><td>0</td><td>0</td><td>0</td><td>0</td><td>0</td><td>0</td><td>0</td><td>0</td><td>0</td><td>0</td><td>0</td><td>0</td><td>0</td><td>0</td><td>0</td></tr>
<tr><td>|TR|</td><td>0</td><td>0</td><td>0</td><td>0</td><td>0</td><td>0</td><td>0</td><td>0</td><td>0</td><td>0</td><td>0</td><td>0</td><td>0</td><td>0</td><td>0</td><td>0</td><td>0</td><td>0</td><td>0</td><td>0</td><td>0</td><td>1</td><td>0</td></tr>
<tr><td>DT</td><td>0</td><td>0</td><td>0</td><td>0</td><td>0</td><td>1</td><td>0</td><td>0</td><td>0</td><td>0</td><td>0</td><td>0</td><td>0</td><td>0</td><td>0</td><td>0</td><td>0</td><td>0</td><td>0</td><td>0</td><td>0</td><td>0</td><td>0</td></tr>
<tr><td>DA+DB</td><td>0</td><td>0</td><td>0</td><td>0</td><td>0</td><td>0</td><td>0</td><td>-1</td><td>0</td><td>0</td><td>0</td><td>0</td><td>0</td><td>0</td><td>0</td><td>0</td><td>0</td><td>0</td><td>0</td><td>0</td><td>0</td><td>0</td><td>0</td></tr>
<tr><td>|DA-DB|</td><td>0</td><td>0</td><td>0</td><td>0</td><td>0</td><td>0</td><td>0</td><td>1</td><td>0</td><td>0</td><td>0</td><td>0</td><td>0</td><td>0</td><td>0</td><td>0</td><td>0</td><td>0</td><td>0</td><td>0</td><td>0</td><td>0</td><td>0</td></tr>
<tr><td>|DR|</td><td>0</td><td>0</td><td>0</td><td>0</td><td>0</td><td>0</td><td>0</td><td>0</td><td>0</td><td>0</td><td>0</td><td>0</td><td>0</td><td>0</td><td>0</td><td>0</td><td>0</td><td>0</td><td>0</td><td>0</td><td>0</td><td>1</td><td>0</td></tr>
<tr><td>PT</td><td>0</td><td>0</td><td>0</td><td>0</td><td>0</td><td>0</td><td>0</td><td>0</td><td>0</td><td>1</td><td>0</td><td>0</td><td>0</td><td>0</td><td>0</td><td>0</td><td>0</td><td>0</td><td>0</td><td>0</td><td>0</td><td>0</td><td>0</td></tr>
<tr><td>PA+PB</td><td>0</td><td>0</td><td>0</td><td>0</td><td>0</td><td>0</td><td>0</td><td>0</td><td>0</td><td>0</td><td>0</td><td>-1</td><td>0</td><td>0</td><td>0</td><td>0</td><td>0</td><td>0</td><td>0</td><td>0</td><td>0</td><td>0</td><td>0</td></tr>
<tr><td>|PA-PB|</td><td>0</td><td>0</td><td>0</td><td>0</td><td>0</td><td>0</td><td>0</td><td>0</td><td>0</td><td>0</td><td>0</td><td>1</td><td>0</td><td>0</td><td>0</td><td>0</td><td>0</td><td>0</td><td>0</td><td>0</td><td>0</td><td>0</td><td>0</td></tr>
<tr><td>|PR|</td><td>0</td><td>0</td><td>0</td><td>0</td><td>0</td><td>0</td><td>0</td><td>0</td><td>0</td><td>0</td><td>0</td><td>0</td><td>0</td><td>0</td><td>0</td><td>0</td><td>0</td><td>0</td><td>0</td><td>0</td><td>0</td><td>1</td><td>0</td></tr>
<tr><td>AT</td><td>0</td><td>0</td><td>0</td><td>0</td><td>0</td><td>0</td><td>0</td><td>0</td><td>0</td><td>0</td><td>0</td><td>0</td><td>0</td><td>1</td><td>0</td><td>0</td><td>0</td><td>0</td><td>0</td><td>0</td><td>0</td><td>0</td><td>0</td></tr>
<tr><td>AA+AB</td><td>0</td><td>0</td><td>0</td><td>0</td><td>0</td><td>0</td><td>0</td><td>0</td><td>0</td><td>0</td><td>0</td><td>0</td><td>0</td><td>0</td><td>0</td><td>-1</td><td>0</td><td>0</td><td>0</td><td>0</td><td>0</td><td>0</td><td>0</td></tr>
<tr><td>|AA-AB|</td><td>0</td><td>0</td><td>0</td><td>0</td><td>0</td><td>0</td><td>0</td><td>0</td><td>0</td><td>0</td><td>0</td><td>0</td><td>0</td><td>0</td><td>0</td><td>1</td><td>0</td><td>0</td><td>0</td><td>0</td><td>0</td><td>0</td><td>0</td></tr>
<tr><td>|AR|</td><td>0</td><td>0</td><td>0</td><td>0</td><td>0</td><td>0</td><td>0</td><td>0</td><td>0</td><td>0</td><td>0</td><td>0</td><td>0</td><td>0</td><td>0</td><td>0</td><td>0</td><td>0</td><td>0</td><td>0</td><td>0</td><td>1</td><td>0</td></tr>
<tr><td>n/2Volmax</td><td>0</td><td>0</td><td>0</td><td>0</td><td>0</td><td>0</td><td>0</td><td>0</td><td>0</td><td>0</td><td>0</td><td>0</td><td>0</td><td>0</td><td>0</td><td>0</td><td>0</td><td>0</td><td>1</td><td>0</td><td>0</td><td>0</td><td>0</td></tr>
<tr><td>1-(n/2Volmax)</td><td>0</td><td>0</td><td>0</td><td>0</td><td>0</td><td>0</td><td>0</td><td>0</td><td>0</td><td>0</td><td>0</td><td>0</td><td>0</td><td>0</td><td>0</td><td>0</td><td>0</td><td>0</td><td>1</td><td>0</td><td>0</td><td>0</td><td>0</td></tr>
<tr><td>V</td><td>0</td><td>0</td><td>0</td><td>0</td><td>0</td><td>0</td><td>0</td><td>0</td><td>0</td><td>0</td><td>0</td><td>0</td><td>0</td><td>0</td><td>0</td><td>0</td><td>0</td><td>0</td><td>0</td><td>0</td><td>0</td><td>1</td><td>0</td></tr>
<tr><td>S</td><td>0</td><td>0</td><td>0</td><td>0</td><td>0</td><td>0</td><td>0</td><td>0</td><td>0</td><td>0</td><td>0</td><td>0</td><td>0</td><td>0</td><td>0</td><td>0</td><td>-1</td><td>1</td><td>0</td><td>0</td><td>0</td><td>0</td><td>0</td></tr>
<tr><td>PC</td><td>0</td><td>0</td><td>0</td><td>0</td><td>0</td><td>0</td><td>0</td><td>0</td><td>0</td><td>0</td><td>0</td><td>0</td><td>0</td><td>0</td><td>0</td><td>0</td><td>0</td><td>0</td><td>0</td><td>0</td><td>0</td><td>1</td><td>0</td></tr>
<tr><td>r</td><td>0</td><td>0</td><td>0</td><td>0</td><td>0</td><td>0</td><td>0</td><td>0</td><td>0</td><td>0</td><td>0</td><td>0</td><td>0</td><td>0</td><td>0</td><td>0</td><td>0</td><td>0</td><td>0</td><td>0</td><td>0</td><td>0</td><td>1</td></tr>
<tr><td>Mean Cycle Time</td><td>0</td><td>0</td><td>0</td><td>0</td><td>0</td><td>0</td><td>0</td><td>0</td><td>0</td><td>0</td><td>0</td><td>0</td><td>0</td><td>0</td><td>0</td><td>0</td><td>0</td><td>0</td><td>0</td><td>0</td><td>0</td><td>0</td><td>0</td></tr>
</table>

Figure 51: Adjacency matrix for the observation ($A_{observation}$)

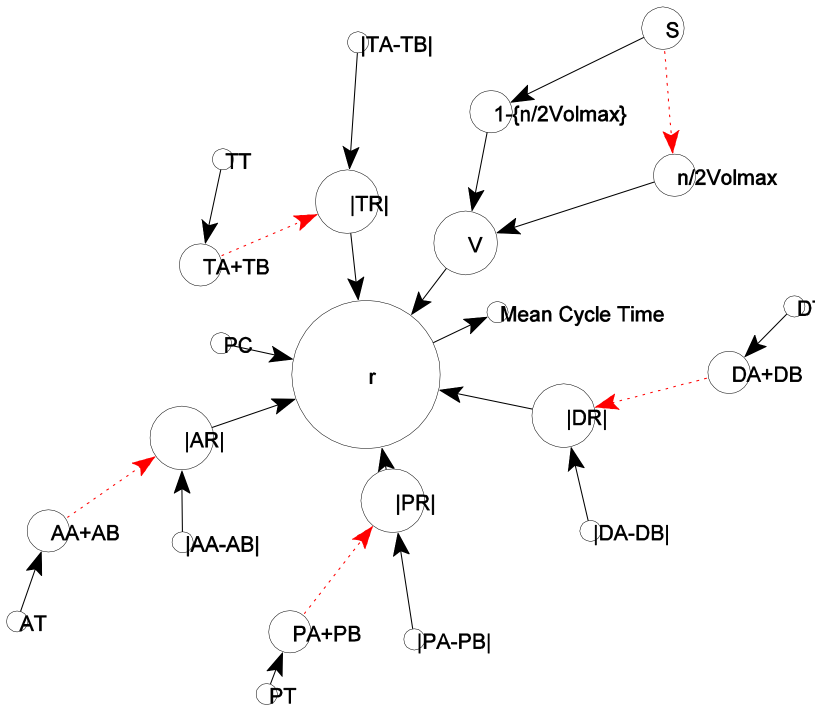


Figure 52: FCM plot for the observation (from $A_{observation}$)

6.3.3 *FCM from interviews integrated with observations*

Codes from the observation FCM are merged with, or linked to, codes in the collective interview FCM. Codes from the collective interview and observation are compared and merged based on Wrightson (1976):

- Does the participant make a distinction between the two things in the interview versus observation? If so, keep the concepts separate. If not, merge the concepts.
- Would the participant believe that the logic had been distorted if the concepts were merged? If so, keep the concepts separate. If not, merge the concepts.
- Are antonyms used? E.g. A/-/ B is the same as –A + B which is the same as A /+/ -B

Examples of this code merging are when the concepts represent the same object (e.g. number of components) or the same event (e.g. the start of the production run).

When comparing the codes from the collective interview and observation, the following scenario must also be accounted for in order to assess the coding similarity between the two fuzzy cognitive maps:

- What if the participant makes a distinction between the two concepts in the interview versus observation (concepts are separate) *and* the logic (between the participant knowledge and practice) would be distorted if the concepts remained separate *and* unrelated?

This question comes up when one code from the collective interview partially describes a code from the observation (or vice versa). For example, the division of work variable from the collective interview FCM (code 20) is embodied in the observation FCM in terms of the distribution of work ratio related to the number of different components |DR|, distribution of work ratio related to the total number of components |TR|, distribution of work ratio related to the number of picking tasks |PR|, and the distribution of work ratio related to the number of assembling tasks |AR|. These examples show that the collective interview code is related to these observation codes, yet the codes are not the same; each of these observation codes partially describes the collective interview code. It makes sense here to enable the codes to remain distinct but to also document their relation with a linkage.

This is an epistemological linkage and its direction is debatable. For example, do the workers separate the number of components between builders (observation codes) because they are employing division of work concepts (collective interview code)? Or do they use division of work concepts (collective interview code) to separate the number of concepts between builders (observation codes)? For the purposes of this analysis, the linkage direction is prudently marked both ways because it represents the reciprocal relationship between the participants' knowledge of a concept and their practice of it. In most FCM practices, each vector is unidirectional because a bi-directional arrow suggests that the concepts are interdependent and should be coded together as one (merged), but this is not done here since the concepts are both distinct and yet need to be related based on logic. FCM practice generally does not integrate multiple data source types, such as observation with collective interviews here, and thus its practice generally does not need to account for this knowledge and practice relation. Table 21 shows how the collective interview codes are merged or linked to the observation codes.

Collective interview concept/code	Link	Observation concept/code
Builders dividing work evenly 20	-1	|TR|
	-1	|DR|
	-1	|PR|
	-1	|AR|
Even out products on each side of the table 42	-1	|TA-TB|
	-1	|DA-DB|
Coordinated actions between builders 83	-1	PR
	-1	AR
Being able to position materials for the assembly process 7	-1	|TA-TB|
	-1	|DA-DB|
	-1	|PA-PB|
	-1	|AA-AB|
Having a designated position for materials around the table 45	-1	|TA-TB|
	-1	|DA-DB|
	-1	|PA-PB|
	-1	|AA-AB|
Total number of components 44	Merged with	TT
Variety of components 34	Merged with	DT
Start production – "ok let's build" 8	Merged with	S
Order size 91	+1	$1-(n/2Vol_{max})$
	-1	$n/2Vol_{max}$
Number of skids 99	+	PC
Assembly process efficiency 5	-1	Mean cycle time

Table 21: Linkages between the collective interview FCM and observation FCM

The code merging and linkages from Table 21 are integrated into the observation adjacency matrix ($A_{observation}$) and then plotted. Variables from the observation adjacency matrix ($A_{observation}$) are in aqua (dark shading), and the merged and linked to variables from the collective interview from Table 21 are in yellow (light shading). The plot is shown in 2D in Figure 53 (to show all of the linkages without crossing would require 3D representation).

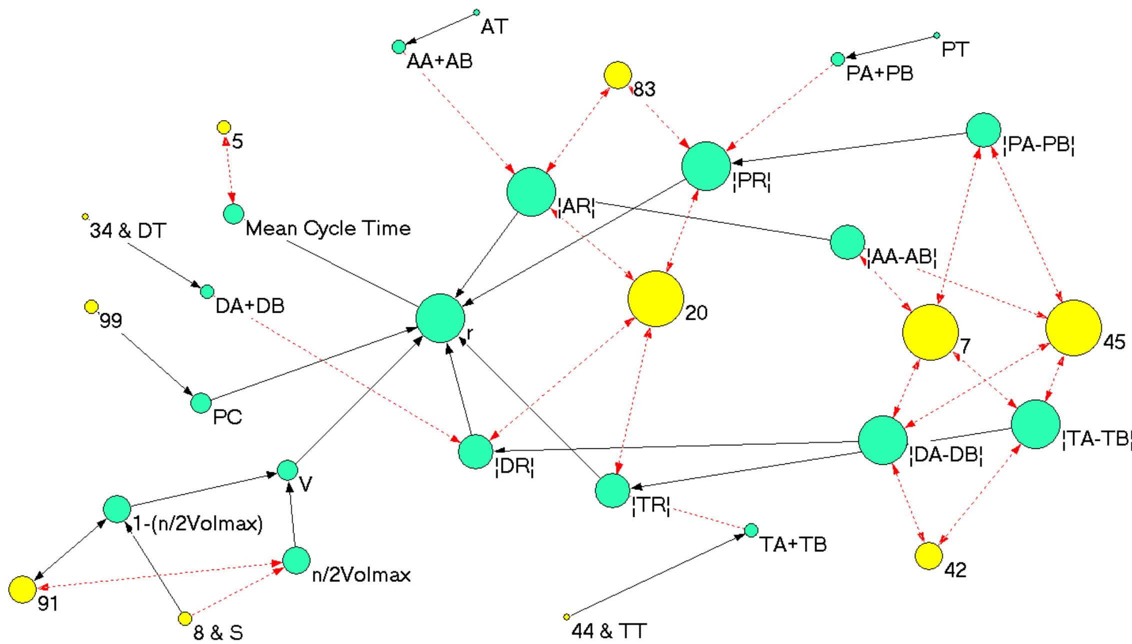


Figure 53: FCM plot for observation (from $A_{observation}$) with collective interview linkages from Table 21

The full collective interview adjacency matrix ($A_{interview(all)}$ with variables in yellow, light shading) and the observation adjacency matrix ($A_{observation}$ with variables in aqua, dark shading) are integrated into an adjacency matrix ($A_{interview(all)\&observation}$). This matrix represents the integrated FCM of knowledge and practice; the plot is shown in 2D in Figure 54 (to show all of the linkages without crossing would require 3D representation).

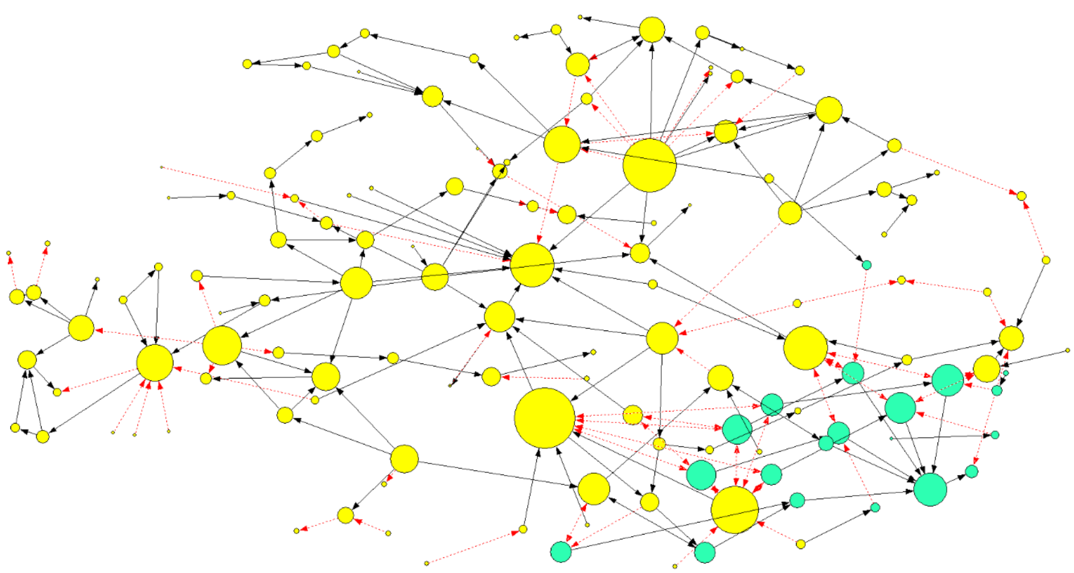


Figure 54: FCM plot for the integrated collective interview and observation ($A_{interview(all)\&observation}$)

6.4 Analysis

With the formulas in §6.2.2.4, the adjacency matrices for the collective interview ($A_{interview(all)}$), observation ($A_{observation}$), and integrated collective interview and observation ($A_{interview(all)\&observation}$) are analyzed along with their FCM plots. The analysis for the collective interview is presented in Table 22, observation in Table 23, and the integrated collective interview and observation in Table 24. The analysis is organized and highlighted per the following five categories:

1) The codes with the top 3 highest out-degree values > 1 (shaded);
2) The codes with the top 3 highest in-degree values > 1 (shaded);
3) The codes with the top 3 highest centrality values > 1 (shaded);
4) The top 3 overall cause concepts (id=0, and od=highest 3 values) (**bold**);
5) The top 3 overall effect concepts (id=highest 3 values, and od=0) (**bold**);
6) The top 3 overall central concepts (c=highest 3 values, id≠0, od≠0) (**bold**);

In the case of a tie within a category, all of the tied codes with that category are included. The highlighted codes unique to one data collection method are indicated with *, and the highlighted codes common with another or integrated method are indicated with +.

Code	Code description	Out-degree $od(v_j)$	In-degree $id(v_j)$	Centrality $c(v_j)$
17	Permanency of workforce +	**12**	0	12
43	Like an assembly line +	6	1	7
63	Forecast accuracy *	5	1	6
64	Order accuracy *	5	2	7
68	Size of customer account +	**5**	0	5
92	Current location of the assembly area (versus past location) +	**5**	0	5
16	Idealness of assembly process +	0	**9.5**	9.5
5	Assembly process efficiency +	0	**4**	4
96	Lead hand availability/utilization +	0	**5**	5
40	Ease of flow of materials *	1.5	6	**7.5**
51	Material handlers pick up finished pallet +	2	7	**9**
27	Assembly components missing *	4	4	**8**

Table 22: Collective interviews FCM analysis ($A_{interview(all)}$)

Code	Code description	Out-degree $od(v_j)$	In-degree $id(v_j)$	Centrality $c(v_j)$
S	Start of production run *	**2**	0	2
TT	Number of total components in the final product assembly *	**1**	0	1
|TA-TB|	Difference of total components that builder A and builder B handle *	**1**	0	1
DT	Number of different components in the final product assembly *	**1**	0	1
|DA-DB|	Difference of different components that builder A and builder B handle *	**1**	0	1
PT	Number of picking tasks for the final product assembly *	**1**	0	1
|PA-PB|	Difference of picking tasks that builder A and builder B perform *	**1**	0	1
AT	Number of assembling tasks for the final product assembly *	**1**	0	1
|AA-AB|	Difference of assembling tasks that builder A and builder B perform *	**1**	0	1
PC	Pallet count *	**1**	0	1
r	Complexity value *	1	6	**7**
|TR|	Distribution of work ratio related to the total number of components *	1	2	**3**
|DR|	Distribution of work ratio related to the number of different components *	1	2	**3**
|PR|	Distribution of work ratio related to the number of picking tasks *	1	2	**3**
|AR|	Distribution of work ratio related to the number of assembling tasks *	1	2	**3**
V	Production phase factor *	1	2	**3**
Mean cycle time	Mean cycle time value *	0	**1**	1

Table 23: Observation FCM analysis ($A_{observation}$)

Note: in the case of the observation adjacency matrix and plot analyzed in Table 23, there is only one overall effect (receiver variable) and only one code with an out-degree value > 1. Also, |TA-TB|, |DA-DB|, |PA-PB|, and |AA-AB| do not remain overall causes in the integrated FCM analysis.

Code	Code description	Out-degree $od(v_j)$	In-degree $id(v_j)$	Centrality $c(v_j)$
7	Being able to position materials for the assembly process *	6	8	**14**
17	Permanency of workforce +	**12**	0	12
43	Like an assembly line +	6	1	7
68	Size of customer account +	**5**	0	5
92	Current location of the assembly area (versus past location) +	**5**	0	5
16	Idealness of assembly process +	0	**9.5**	9.5
51	Material handlers pick up finished pallet +	2	7	9
5	Assembly process efficiency +	0	**4**	4
96	Lead hand availability/utilization +	0	**5**	5
20	Builders dividing work evenly *	5	5	**10**
45	Having a designated position for materials around the table *	5	6	**11**

Table 24: Integrated collective interview and observation FCM analysis ($A_{interview(all)\&observation}$)

The fuzzy cognitive mapping results are further analyzed using the latter formulas in §6.2.2.4, the adjacency matrices for each interview ($A_{interview}$), the collective interview ($A_{interview(all)}$), observation ($A_{observation}$), and integrated collective interview and observation ($A_{interview(all)\&observation}$) are analyzed along with their plots. To analyze the complexity of information, the types of variables in each fuzzy cognitive map are first identified. Transmitter variables have only an out-degree. Receiver variables have only an in-degree. Ordinary variables have both an in-degree and out-degree. Several perspectives on complexity as outlined in §6.2.2.4 are calculated: a receiver to transmitter ratio; the number of nodes; the number of linkages; the linkage to node ratio; the ordinary variable to node ratio; and the density of the fuzzy cognitive map. These results are summarized in Table 25.

FCM of	# of Transmitter Variables (T)	# of Receiver Variables (R)	# of Ordinary Variables (OV)	Complexity Ratio (R/T)	# of Nodes (N)	# of Linkages (L)	L/N	OV/N	Density (D)
$A_{interview1}$	4	7	7	1.8	18	17	0.9	0.4	0.06
$A_{interview2}$	2	2	1	1.0	5	4	0.8	0.2	0.20
$A_{interview3}$	5	2	2	0.4	9	9	1.0	0.2	0.13
$A_{interview4}$	3	4	8	1.3	15	15	1.0	0.5	0.07
$A_{interview5}$	14	3	9	0.2	26	25	1.0	0.3	0.04
$A_{interview6}$	1	4	8	4.0	13	14	1.1	0.6	0.09
$A_{interview7}$	10	13	6	1.3	29	26	0.9	0.2	0.03
$A_{interview8}$	14	17	24	1.2	55	63	1.1	0.4	0.02
$A_{interview(all)}$	34	27	59	0.8	120	161	1.3	0.5	0.01
$A_{observation}$	10	1	12	0.1	23	23	1.0	0.5	0.05
$A_{interview(all)\&observation}$	35	25	80	0.7	140	224	1.6	0.6	0.01

Table 25: FCM adjacency matrix analysis (interviews, observation, and integrated)

The results in Table 25 show that for the different methods of calculating information complexity, the general trend is for the integrated FCM to be more complex than the collective interviews and observation FCMs. The analysis in Table 25 also highlights that the integrated FCM is a synthesis of the collective interview and observation FCM, not an addition (e.g. for linkages 23+161=184≠224). This highlights that the emic investigative approach develops a holistic model of the socio-technical system: the whole is more than the sum of the parts. The collective interview, observation, and integrated FCM analyses in Table 22 – Table 24 also support this idea, where their separate analyses share similarity and differences between one another (indicated by the + and * symbols). There is, however, no universal measure of complexity to relate the results in Table 25 to: “cognitive maps can be representing reality successfully even if they are not highly complex” (Özesmi and Özesmi, 2004, p.59). Qualitatively, the maps can be evaluated by discussing their meaning, as in §6.5.

6.5 Discussion

The results are first discussed in terms of the chapter’s first research question: How can a socio-technical system be modeled from operator participation and how does it benefit re-design?

The proposed emic investigative approach engages participants (18 here) in holistically modeling the socio-technical system as follows. Data on the participants' knowledge and practice of operating the socio-technical system is collected in situ via interview and observation respectively. This data is analyzed with fuzzy cognitive mapping by accounting for various parts (e.g. participant and data perspectives) and the whole with holism because the parts are linked relationally and synthesized rather than added. Assembly cycles are synthesized into observation sets, which are synthesized with statistical analysis, further synthesized with coding into an operational model and observation adjacency matrix. Interviews are coded, which are merged across interviews, further synthesized into a collective interview adjacency matrix. The collective interview and observation adjacency matrices are synthesized to form an integrated adjacency matrix. These adjacency matrices and their plots model the socio-technical system, accounting for concepts (nodes/codes) and relationships (linkages) with parts, between parts, and across the whole derived from operator participation (the emic/insider perspective). This is a significant strength of the investigative approach and a direct outcome of integrating mixed methods with FCM grounded in the participants' knowledge and practice of operating the socio-technical system.

This approach defines a socio-technical system model that benefits the re-design process because it makes the existing system explicit, identifying concepts and their inter-relationships that explain the system behaviour (inputs, operations, constraints, and outputs); the principles that govern the system behaviour; the function that relates the behaviour to the context; and the structure that the system behaviour reflects (per Figure 42). These insights are further synthesized into re-design clauses and foci to be utilized in subsequent stages of the socio-technical system re-design process, to continue the re-design process with a holistic approach. These benefits are further outlined here for the socio-technical system model in the re-design project at hand, which answers the chapter's second research question: What is the socio-technical system model in the re-design project at hand?

6.5.1 *Overall cause concepts in the STS model – inputs, constraints, principles*

The overall causes in the socio-technical system model (id=0, and od=highest 3 values) exist at the immediate socio-technical system boundary, moving from an outside system (input or external constraint) or from the inner limits of the immediate system's boundary (internal constraint) into the immediate system. The overall causes in the collective interview (Table 22), observation (Table 23), and integrated (Table 24) FCM analyses are organized into Table 26.

Overall causes (code, description)	Input	Constraint	Collective interview	Observation	Integrated collective interview and observation
S, Start of production run	x			x	
TT, Number of total components in the final product assembly	x			x	
DT, Number of different components in the final product assembly	x			x	
PT, Number of picking tasks for the final product assembly	x			x	
AT, Number of assembling tasks for the final product assembly	x			x	
17, Permanency of the workforce		x	x		x
68, Size of customer account		x	x		x
92, Current location of the assembly areas (versus past location)		x	x		x

Table 26: Overall cause concepts in the FCM analyses

For the inputs in Table 26, TT and DT represent material; S represents information or a signal; and PT and AT represent material here because they represent in this case how the assembly components are pre-packaged (from a system external to the immediate one being studied). For the constraints in Table 26, the permanency of the workforce and the size of customer account are external constraints (they are determined outside of the immediate system in the broader business context); and the current location of the assembly area is a space constraint within the immediate system.

In addition to the overall cause concepts in Table 26, the FCM analysis for the collective interview (Table 22) also identifies high out-degree for forecast accuracy, order accuracy, and the concept "like an assembly system." The forecasts and orders are information inputs to the system; the quality of this information (accuracy) impacts the system when it's utilized. The concept "like an assembly system" is a participant described system principle for re-design. It is a desired intent for the system behaviour driven by the overall cause concept "applies to us." Participants cite that it will affect the amount of work for builders; amount of work for lead hands (putting components onto the assembly line); amount of work for material handlers (putting components onto the assembly line); ease of flow of material(s); a new machine; and the ease of assembly work. In other words, the intent of the re-design principle "like an assembly line" is not to simply create an assembly line; the intent is to adapt the assembly line paradigm in light of the concerns about it. This is a significant insight into the re-design process and one the designer must bear in mind if the re-design is to be successful. It's also a very insightful shift about design thinking – the intent of the re-design is not a universal solution but rather a differentiated one that "applies to us" ("us" being participants and socio-technical system operators).

6.5.2 Overall effect concepts in the STS model – outputs and function

The overall effects in the socio-technical system model (id=highest 3 values, and od=0) exist at the immediate socio-technical system boundary, moving to an outside system (output) or to the inner limits of the immediate system's boundary (function) from within the system. The overall causes in the collective interview (Table 22), observation (Table 23), and integrated (Table 24) FCM analyses are organized into Table 27.

Overall effects (code, description)	Output	Function	Collective interview	Observation	Integrated collective interview and observation
Mean cycle time		x		x	
5, Assembly process efficiency		x	x		x
16, Idealness of assembly process	x	x	x		x
96, Lead hand availability/utilization			x		x

Table 27: Overall effect concepts in the FCM analyses

For the function in Table 27, the mean cycle time and assembly process efficiency reflect the specific function of the STS – the rate at which the inputs are transformed into outputs via human-object relations. The idealness of the assembly process is a concept defined by the participants as an aggregate of both system function and output (as well as, more broadly, behaviour). Participants state that an ideal assembly process is achieved (as an effect) from such concepts as builders making decisions about work as partners, working conditions that one participant described as "chivalry," and meeting constraints (such as the current location of the assembly area, permanency of the workforce, ease of flow of material) to assemble final assemblies without any components missing.

It's interesting that the code "lead hand availability/utilization" appeared here as an overall effect, so the FCM maps were investigated for further explanation. The code is phrased in several ways, including its negative "don't come and get lead hand." In other words, it represents a potential dead end in the system if the other operators do not come and get the lead hand when they need him/her (e.g. if they have a question). When found in its positive the code also embodied answering questions, for example, so it is part of a more central behaviour that contributes to function in its positive.

6.5.3 Overall central concepts in the STS model – operations and constraints

The overall central concepts in the socio-technical system model (c=highest 3 values, id≠0, and od≠0) exist in the middle of the socio-technical system, moving between and within the system's boundary (operations and internal constraints that affect operations). The overall causes in the collective interview (Table 22), observation (Table 23), and integrated (Table 24) FCM analyses are organized into Table 28.

Overall central (code, description)	Operations	Constraints	Collective interview	Observation	Integrated collective interview and observation
40, Ease of flow of materials		x	x		
51, Material handlers pick up finished pallet	x		x		
27, Assembly components missing in the final assembly		x	x		
r, complexity value	x			x	
|TR|, Distribution of work ratio related to the total number of components	x			x	
|DR|, Distribution of work ratio related to the number of different components	x			x	
|PR|, Distribution of work ratio related to the number of picking tasks	x			x	
|AR|, Distribution of work ratio related to the number of assembling tasks	x			x	
V, Production phase factor	x			x	
7, Being able to position materials for the assembly process	x				x
20, Builders dividing work evenly	x				x
45, Having a designated position for materials around table	S				x

Table 28: Overall central concepts in the FCM analyses

For the constraints in Table 28, the "ease of flow of material" is a form of precedence that affects the assembly production operations e.g. if you don't have the assembly components, you can't perform the picking or assembling tasks. The "assembly components missing" in the final product assembly is also a constraint affecting operations because assembly production is not complete until the final product assembly has the correct components. If it's discovered that an assembly component is missing, then the builders and lead hands have to stop the assembly process and determine where the error was made and rectify it (constraining the operations in the assembly production system).

The operations in Table 28 consist of human-object entities within the socio-technical system, e.g. material handlers picking up the finished pallet; the distribution of work ratios related to the total number of components, number of different components, number of picking tasks, and number of assembling tasks, etc. The operations of the socio-technical system relate to the inputs, outputs, and constraints in §6.5.1 and §6.5.2 to describe the system behaviour. These operations also relate to the structure of the system, e.g. in Table 28 "having a designated position for materials around the table" relates the STS operations to the layout structure in the assembly production system. These relations can further be synthesized into re-design foci in the re-design process.

6.5.4 Socio-technical system re-design foci and clauses

The socio-technical system behaviour is a relationship between the inputs and constraints in §6.5.1; outputs in §6.5.2; and operations and constraints in §6.5.3. This behaviour reflects the system structure, grouped here as process, layout, and training in the STS model in the re-design project at hand. The differentiated design principle that is intended to govern the system behaviour in the re-design project at hand, in addition to the STS concept, is identified in §6.5.1. The system function that relates the behaviour to the context is identified in §6.5.2.

These insights are further synthesized into re-design clauses and foci to be utilized in subsequent stages of the socio-technical system re-design process, to continue the re-design process with a holistic approach. The idea of a re-design clause is useful here because it summarizes the analysis of the participant expressions of knowledge and practice so that it can be re-expressed back to the participants as a social agreement in the re-design process.

Re-design foci	Re-design clauses	
	#	Clause
Layout	1	Existing space is a constraint. In this situation, the re-design seeks to better utilize the existing space to position materials for better flow while addressing that it's challenging to have designated positions for materials due to the variety of assembly components and final product assemblies.
Process	2	The re-design seeks to engage builders to transform the input signals/information (start of production run, orders) and materials (components) into final product assemblies with no components missing. This is accomplished through central human-object operations (e.g. the distribution of work). Together, this behaviour performs the system function, as observed in cycle time (a measure of efficiency). The division of work between builders affects, and is affected by, the distribution of the components and picking and assembling tasks, which also affects and is affected by the positioning of the components. The re-design aims to address this inter-relationship between layout and process to accomplish clause #1 and clause #2 synergistically.
Training	3	The impermanent builder position is a constraint. In this situation, the re-design seeks to improve the existing builder training practices with consideration for the training time to ensure that builders know what to do in the assembly process especially in regard to quality (ensuring that assembly components are not missing in the final product assembly).
Different-iated design	4	To accomplish re-design clauses #1-3, the re-design process is intent on working with stakeholders to ensure that the re-designed assembly system "applies to us" (differentiated design). This participatory re-design process begins with these four design clauses, which inform our social contract with one another as the re-design tasks that we are engaged in resolving together. In doing so, the re-design process is also committed to the continued work culture, described as "chivalry."

Table 29: Re-design foci and clauses

The re-design foci and clauses in Table 29 define how the socio-technical model, developed with the emic investigative approach in §6.2, provides direction to subsequent steps in the re-design process as well as documenting the current system. This ability to capture the current state of the socio-technical system in a reference model enables a comparison to be made before vs. after a re-design intervention, to measure the intervention's impact on the system.

6.6 Conclusion

This chapter provides an emic investigative approach for modeling a socio-technical system holistically from operator participation outlined in §6.2. The approach engages participants (STS operators) in discussing (in interview) and showing (in observation) how they operate the socio-technical system (in this case an assembly production system and STS archetype). This data is then analyzed and synthesized with fuzzy cognitive mapping to identify concepts and their inter-relationships that model the socio-technical system by explaining its behaviour (relating inputs, operations, constraints, and outputs), function, structure, and principles. In the STS re-design project at hand, the STS model is described in §6.3, analyzed in §6.4, and discussed in §6.5. This investigative approach is a new application of FCM that integrates observation and interview for emic system modeling, contributing to the FCM literature.

The emic investigative approach's ability to make the existing system design explicit in a STS model is essential to re-designing a socio-technical system because it is a living system; system operators are within the system and are part of the human-object relations with which the system operates. This means that re-design involves transforming the existing system into the subsequent system.

The emic investigative approach makes this possible by explicating the existing system and then utilizing the model to inform re-design. This is achieved by synthesizing the FCM and model analysis into re-design foci and clauses for a social agreement in re-design between the designers and participants, supporting the next steps in the STS re-design process. In the re-design project at hand, four re-design foci (process, layout, training, and differentiated design) and their clauses were found to support the next steps in the re-design project. These re-design foci, clauses, and system reference model inform co-design (Chapter 7) and provide a means and basis to evaluate the co-design impact in before versus after comparison (Chapter 9). The trustworthiness and validation of this chapter research are evaluated in Chapter 11. The limitations of this chapter research are examined in Chapter 12.

Based on these conclusions, "Emic system modeling" is a critical step after "Ethical considerations for participation" (Figure 29, Chapter 4) in this dissertation's model for re-designing a socio-technical system, summarized systematically with an IDEF0 model in Figure 55. Figure 55 is related to the research questions in the dissertation study as follows. The inputs, mechanisms, and reference models relate to research question 2 (shown in Figure 55 in `Courier font`). The questions, outputs, and constraints relate to research question 3 (shown in Figure 55 in Calibri font).

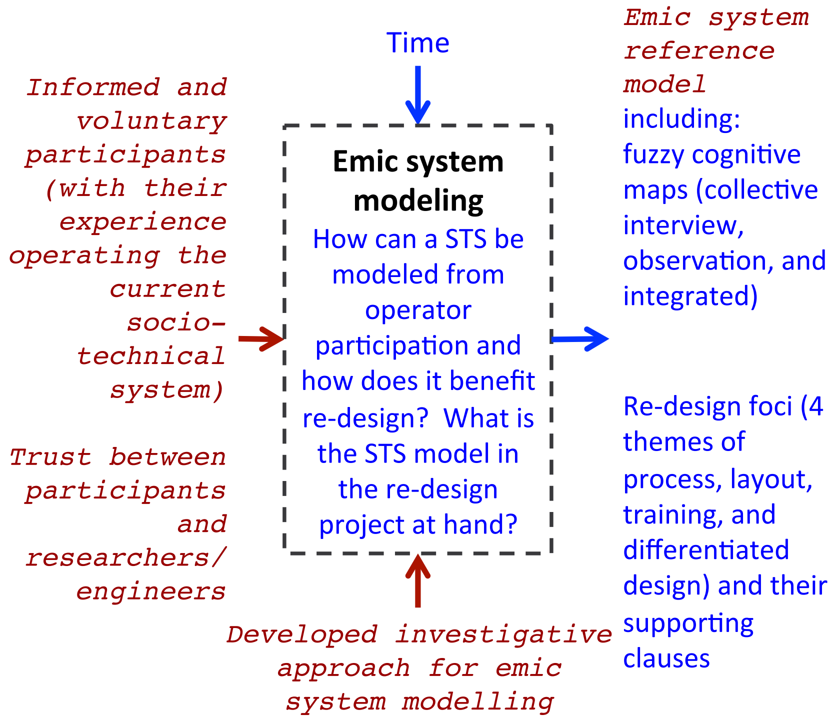


Figure 55: Emic system modeling IDEF0

The position of "Emic system modeling" (Figure 55) in this dissertation's model for re-designing a socio-technical system is shown in Figure 56.

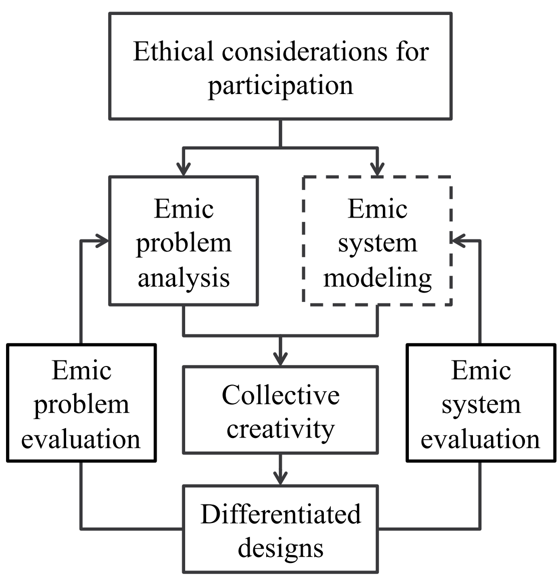


Figure 56: Emic system modeling in the developed model for re-designing a socio-technical system

7 Collective creativity in socio-technical system re-design

The output of emic problem analysis (Chapter 5) and emic system modeling (Chapter 6) is utilized in the next step in developing a participatory approach for re-designing a socio-technical system – co-designing solution variants with participants. Solution variants are developed in system synthesis in engineering design methodology (Pahl et al., 2007, p. 16) and systems design methodology (Whitten and Bentley, 2007, p. 30). Co-design has only been explicitly related to STS theory in relation to system modeling (Clancey, 1993) and has not been explicitly related with re-design for co-designing solution variants (Table 5).

In turn, the research in this chapter asks: How do participants take action to co-design solution variants in STS re-design? The focus of this chapter is on "how" and Chapter 8 focuses on "what" (the solution variants). This chapter investigates this question with an emic (insider/participant) orientation, grounding the research in qualitative methodology (§3.2) and developing the support study of design research methodology (§3.1, Figure 6). The intention here is to explore this chapter's research questions *in situ* in the re-design of an assembly production system and socio-technical system archetype. The industrial context and participants are described in §3.4.

Co-design is a form of participatory design, discussed in §3.3.1, and defined as "collective creativity as it is applied across the whole span of a design process" (Sanders and Stappers, 2008, p.6). The study of collective creativity is an important one in light of its growing popularity and promise. In 2014, Taylor declared the "power to create" as an unprecedented opportunity of human progress (p.2), in his annual lecture as Chief Executive of the *Royal Society for the Encouragement of Arts, Manufactures and Commerce* (RSA). Therein, Taylor (2014) described creativity as an individual and social duality: "prizing creativity means honouring the individual" (p.3) while "part of our creativity lies in the plurality of our social existence" (p.12). Both perspectives are particularly relevant to participatory design, since it is predicated on the values of participant say and social interaction.

Accordingly, co-design is both a method for promoting collective creativity and a situation in which it can be studied. To inquire into this intersection of PD and collective creativity, researchers have developed shared mental models of group interaction. These mental models have uncovered critical aspects of collective creativity, such as collective emergence in design (Shaw, 2010), how to assist and capitalize on creativity (Alberti, Dejean, and Cayol, 2007), and towards understanding design team communication (Reid and Reed, 2005), cognition and performance (Badke-Schaub et al., 2007). It is clear from these examples that "the value of a model lies in its ability to help us organize our thoughts and gain insight into important aspects of reality" (Hyman, 1998, p. 7) concerning, here, collective creativity.

In the research presented here, the reality of collective creativity is regarded as a shared experience that can be understood by the participants' actions in co-design. In the re-design project at hand, this means co-designing solution variants in re-designing an assembly production system with 11 participants. Accordingly, the aim of the research presented here is not to determine a shared mental model per se. Rather, the aim is to create a shared action model -- explicating how collective creativity occurs by coding participants' actions into a de facto representation of the shared co-design experience, thereby conceptualizing the individual and social duality. Since participatory design is action-oriented and centered on practice, an action model is quite fitting. It is also quite useful for questioning design thinking since actions allow for direct comparison – to the actions intended in other methods for creativity and ideation in design.

Accounts estimate as many as 172 different methods of ideation (Smith, 1998). Several ideation approaches are summarized in a glossary by Gonçalves, Cardoso, and Badke-Schaub (2014) and within a number of design texts, e.g. in engineering (Chakrabarti, 2002; Cross, 2008) and in industrial design (Hanington and Martin, 2012; Kumar, 2012). Brainstorming (Osborn, 1953) is cited as one of the most commonly used methods for ideation in design (Kelley, Littman, and Peters, 2001), which several authors have further reviewed and analyzed (Byron, 2012; Matthews, 2009). Consequently, this chapter research also asks: How does the model of participant action(s) in collective creativity (in co-designing solution variants in STS re-design) compare with brainstorming?

This chapter sets out to develop a model of participant actions in collective creativity from their participation in the co-design of solution variants in STS re-design. The investigative approach is outlined in §7.1. It begins with collecting participant action data from two co-design events, which are motivated by the emic problem statement and re-design foci (from the emic problem analysis in Chapter 5 and emic system modeling in Chapter 6). This data is then analyzed with adapted fuzzy cognitive mapping (FCM) techniques, which involve coding, adjacency matrices, and plots. The FCM results (§7.2) are analyzed in (§7.3) to reveal the model of participant actions in collective creativity (§7.4). Features of the model are then discussed and compared with brainstorming (§7.5), which highlight that the participants' model of collective creativity creates, assesses, and contextualizes solution variants.

7.1 The participant action model investigative approach

The investigative approach for modeling the participant actions in the co-design of solution variants in STS re-design is outlined in Figure 57.

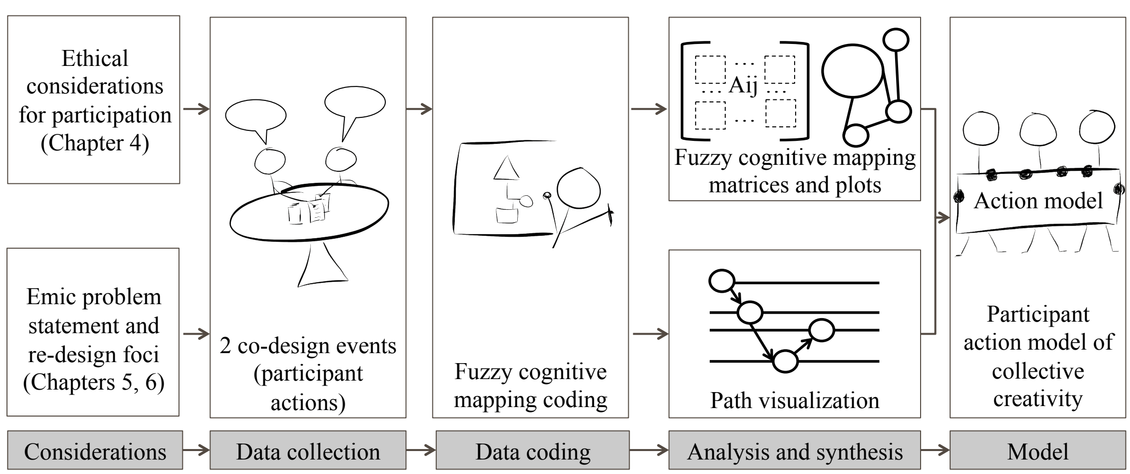


Figure 57: The participant action model investigative approach

The following sections (§) align with the investigative approach in Figure 57 as follows. First, the co-design events and data collection are described (§7.1.1). Fuzzy cognitive mapping (FCM) is briefly described (§7.1.2) and decomposed in terms of coding (§7.1.2.1) followed by adjacency matrices, plots, and analysis (§7.1.2.2).

7.1.1 Co-design events and data collection

Three co-design events were held. The first two events are discussed in this chapter; the third event is discussed in Chapter 8 and is a continuation of the second event. The co-design events discussed in this chapter are motivated by the emic problem analysis (Chapter 5) and emic system modeling (Chapter 6) and their alignment. The emic problem statement from Chapter 5 is: the stakeholders (builders, lead hands, supervisor, planner, and manager) need a re-designed assembly process “that applies to us” with a focus on process, layout, and training because of eight critical problem foci and the related 26 concern web.

The themes of process, layout, and training in the emic problem statement are also the first three re-design foci from the emic system modeling. These re-design foci are further described by the re-design clauses supporting each. Similarly, these themes are further described by the eight critical problem foci supporting each (four relate to process, two relate to layout, and 2 relate to training). Process, layout, and training are the subject for the co-design events, motivated by their re-design clauses and critical problem foci, as outlined in Table 30 to Table 32.

The “applies to us” concept in the emic problem statement is the fourth re-design foci from the emic system modeling – differentiated design. This re-design principle informs, and is utilized for, the co-design events by emphasizing a “you” orientation in asking questions. This is outlined in the critical questions in Table 30 to Table 32.

Process co-design foci	
Motivation	Four critical problem foci related to process (codes 14, 19, 11, and 15): • 14 – improve flow • 19 – improve build sequence and division of work • 11 – ensure quality of final assemblies (no post-inspection) • 15 – streamline assembly process, more efficient Clause for the process re-design foci: The re-design seeks to engage builders to transform the input signals/information (start of production run, orders) and materials (components) into final product assemblies with no components missing. This is accomplished through central human-object operations (e.g. the distribution of work). Together, this behaviour performs the system function, as observed in cycle time (a measure of efficiency). The division of work between builders affects, and is affected by, the distribution of the components and picking and assembling tasks, which also affects and is affected by the positioning of the components. The re-design aims to address this inter-relationship between layout and process to accomplish clause #1 and clause #2 synergistically.
Goals	To develop, analyze, and re-develop ideas for your assembly process design relating to: actions, methods, tools, tasks, sequencing of tasks, grouping of tasks, and breakdown of tasks.
Critical questions	In your building process… • How do you want to select the components each time that you build an assembly? • How do you want to put the components of the assembly together (assemble them)? • How will you ensure that you have selected the right components for the order and have put them together according to the work order (ensuring quality)? What would make [choosing the components, putting the components together, ensuring quality] easiest for you and your fellow workers?

Table 30: Motivation, goals, and critical questions for the process co-design foci

Layout co-design foci	
Motivation	Two critical problem foci related to layout (codes 12 and 13): • 12 - Working with limited room and space • 13 - Organize and designate position for materials (staging) Clause for the layout re-design foci: Existing space is a constraint. In this situation, the re-design seeks to better utilize the existing space to position materials for better flow while addressing that it's challenging to have designated positions for materials due to the variety of assembly components and final product assemblies.
Goals	To develop, analyze, and re-develop ideas for your assembly process layout design relating to: • Designating layout areas (e.g. we need an area for this (and this)); • Locating layout areas (e.g. we need an area here); • Describing contents for layout areas (e.g. we need these things in this area); • Dimensioning layout areas (e.g. we need an area this big for these things); • Positioning layout areas (e.g. we need an area for this next to this); • Orienting layout areas (e.g. we need this facing…); and • Analyzing flow (e.g. we need to bring things into/out of the area in this direction).
Critical questions	In your space… • Where do you want to select the components? • Where do you want to assemble the components? What would make [getting the components, receiving the components] easiest for you and your fellow workers?

Table 31: Motivation, goals, and critical questions for the layout co-design foci

Training co-design foci	
Motivation	Two critical problem foci related to training (codes 9 and 10): • 9 – Training builders • 10 – Establish builder responsibility and autonomy Clause for the training re-design foci: The impermanent builder position is a constraint. In this situation, the re-design seeks to improve the existing builder training practices with consideration for the training time to ensure that builders know what to do in the assembly process especially in regard to quality (ensuring that assembly components are not missing in the final product assembly).
Goals	To develop, analyze, and re-develop ideas for training on the re-designed assembly process and layout relating to: • What needs to be known about the process and layout in different roles (knowledge, skills, and values); • Relationships between what needs to be known (e.g. precedence/scaffolding); and • Effective means of learning.
Critical questions	Based on your experience with the re-designed process and layout (demonstration, testing, observation, etc.): • What is important to consider in the training design? • Are there any questions that you think we should answer together while we design the training? • What are the process steps in the process and what are different people doing at each of the steps? What do different people need to know at each of these steps? • What form should this training take? • Based on your ideas, what forms of training do we want to begin to design? • How would you describe your experience with participatory design? As you're designing, keep yourself and your fellow workers in mind – what's important to you and your fellow workers?

Table 32: Motivation, goals, and critical questions for the training co-design foci

Information in Table 30 to Table 32 was shared with each participant in a handout (Appendix I, J, and K) to make the design of the event transparent; in doing so, the researcher/facilitator also encouraged the participants to make the event their own and utilize the outlines as a starting point. Accordingly, the co-design event was wholly grounded in the participants' views of the assembly production system and was thus not only an opportunity for the participants to take action in re-designing it, but to take collective action on the interests and concerns that they first expressed individually. In other words, the co-design event was not an instrument of the designers for participants, nor was it an instrument of the participants for designers; it was an instrument of exchange between participants and designers.

Since there were several mutual motivations, goals, and critical questions involved in re-designing the assembly production system process and layout (Table 30 and Table 31), they were explored together in the first co-design event (PD1&2) with 7 participants. Since the training design was dependent upon the process and layout re-designs, it was explored in the second co-design event (PD3) with 9 participants. The participant groups for the two events were not identical, though several participants were part of both. The events took place on two separate days for more than two hours each.

In addition to the motivations, goals, and critical questions that structure the co-design events, the methods of learning were also intentionally designed to support mutual learning between designers and participants. The first co-design event (PD1&2) focused on engaging participants in discussion and experiential simulation by holding the event in the production area where participants could experiment with their work environment directly. This is important to the context because the design of manufacturing systems, including assembly systems, is greatly influenced by scale. Encouraging participants to employ the physical environment created an opportunity for participants to learn directly in relation to scale, to test and trigger new ideas (e.g. moving tables, arranging pallets, selecting assembly components, etc.). The second co-design event (PD3) continued from the previous event, beginning in the production environment. The event began with a demonstration of the re-designed layout and process where any new participants (due to shift work and the temporary build position) could ask questions and engage in discussion. In a conference room, participants then reflected on the demonstration by writing their thoughts on the first two critical questions (Table 32). Participants then engaged in sharing their reflections around the table, which flowed into group discussion. At the end of the event, the participants worked in groups on the ideas that they selected to work on in more detail.

Both co-design events utilized a number of active, experiential learning methods, in various combinations and approaches. The methods and approaches included experiential simulation with observation, group discussion, discussion with simulation, demonstration, reflection, writing, thinking aloud while doing, and hands-on or kinesthetic learning. They align with the PD emphases on collective and individual action, hands-on doing, and reflection in action. Critical to kinesthetic learning was the materials that the participants worked with (often referred to as manipulatables in the participatory design literature), which are outlined in Table 33.

Boxes	Timer	Chart paper
Twine	Velcro	Coloured markers
Pallets	Scissors	Packing tape and dispenser
Hand lift	Foam board	Different coloured electrical tape
Construction paper	Work table	Other materials as requested by
Assembly components	Post-it notes	participants

Table 33: Co-design event materials

At the beginning of each co-design event, participants were reminded that they could voluntarily withdraw from the research without consequence at any time. Mutual expectations were also discussed at the beginning – to respect one another and to value everyone's ideas. Data was collected from the co-design events via observation notes; reflections taken immediately after the event; group notes written on chart paper during the event; design artefacts that the participants produced; and participant notes including reflections and observations. Relating these various sources of evidence has provided rich data that was subsequently coded for fuzzy cognitive mapping (FCM).

7.1.2 Fuzzy cognitive mapping

Since fuzzy cognitive mapping (FCM) is discussed in detail in Chapter 6 §6.2.2, an abbreviated summary is given here. Papageorgiou and Salmeron (2014) establish that fuzzy cognitive mapping has a wide scope of applicability, particularly useful in modeling complex systems with existing knowledge and human experience in a flexible, adaptable, and easy to use approach. This complexity and experiential sensitivity make it suitable for modeling the actions of collective creativity in the shared co-design experience.

The FCM technique proceeds as follows. FCM begins with coding data to identify relationships in the form of cause concept/linkage/effect concept. The linkage is given a value between -1 and 1, integrating fuzzy logic where appropriate. The coding is then transferred into an adjacency matrix composed of causes (rows), effects (columns), and corresponding linkage values. This adjacency matrix is then plotted as a di-graph with cause and effect concepts (nodes) and linkages (arrows or vectors). The adjacency matrices and FCM plots are particularly useful for the purposes of this research to analyze and synthesize participant actions holistically.

7.1.2.1 FCM coding

The coding method for cognitive mapping is a type of content coding, outlined in detail by Wrightson (1976) in Axelrod's (1976) cognitive mapping body of work. Wrightson's (1976) coding method is summarized here into *four necessary considerations* that are structured into questions and answered in this research context. These questions are then integrated into a coding process that was applied to the co-design event data.

Was there a relationship? In this case, since an event was coded the chain of participant actions was considered (X then Y then Z). This created the relationships X→Y and Y→Z (Y becomes both a cause and an effect). If there was a clear inter-relationship between two actions (e.g. a question followed by an answer, a need followed by and an idea that addresses that need, etc.), then they were considered to be linked. If the inter-relationship was unclear, then the two actions were not considered to be linked. This translated into FCM terminology as: cause concept/linkage/effect concept.

What were the concept(s)/actions? A concept must be able to take on a value. Concepts can also be events, where the value is in terms of it occurring or not. For this research, each action taken within the event was coded in its time order. An action was defined as a statement that was made or a physical action that was taken (e.g. a moved or arranged object). The concepts were isolated. To avoid confusion between concepts in the design process and concepts in the FCM coding, FCM concepts in this research have been termed "actions."

What was the cause action? What was the effect action? For this research, the sequence of actions (per step 1) determined that the preceding action was the cause and the subsequent action was the effect.

What was the linkage (relationship) symbol and its logic value between the cause action and the effect action? Since this study only coded actions that occurred, and only linked actions that had clear inter-relationships, each linkage was given a positive (+) symbol and value of 1. In the FCM literature, coding can sometimes contain decimal values (fuzzy logic) and the possibility for negative relationships; this pertains to situations outside the scope of the research presented here (e.g. a textual analysis where a participant describes something that shouldn't happen, or isn't likely to happen, or may not happen, etc.).

For this research, Wrightson's (1976) coding method was adapted for frequency. In the general rules for FCMs, redundant linkages are not added. As a result, typical FCM linkages are quantified between -1 and 1. In this research study, the frequency of a linkage was studied to quantify redundancy as an indicator of the relationship strength; as a result, when a relationship occurred more than once in the data, the linkage values were added (1+1…).

In addition to this adaptation, it should be noted that the terms 'cause' and 'effect' have been used lightly in this research. For example, it is an overly simplistic cognitive model to view a question causing an answer. For this research, a 'cause' has been considered an action that clearly precedes, or leads to, the subsequent action. An 'effect' has been considered an action that clearly proceeds from, or follows, the previous action. The terms 'cause' and 'effect' have been used in this research for consistency with the FCM method, but the differentiated use of these terms warrants attention.

The data collected from the co-design events (PD1&2 and PD3) was coded with the process in Figure 58.

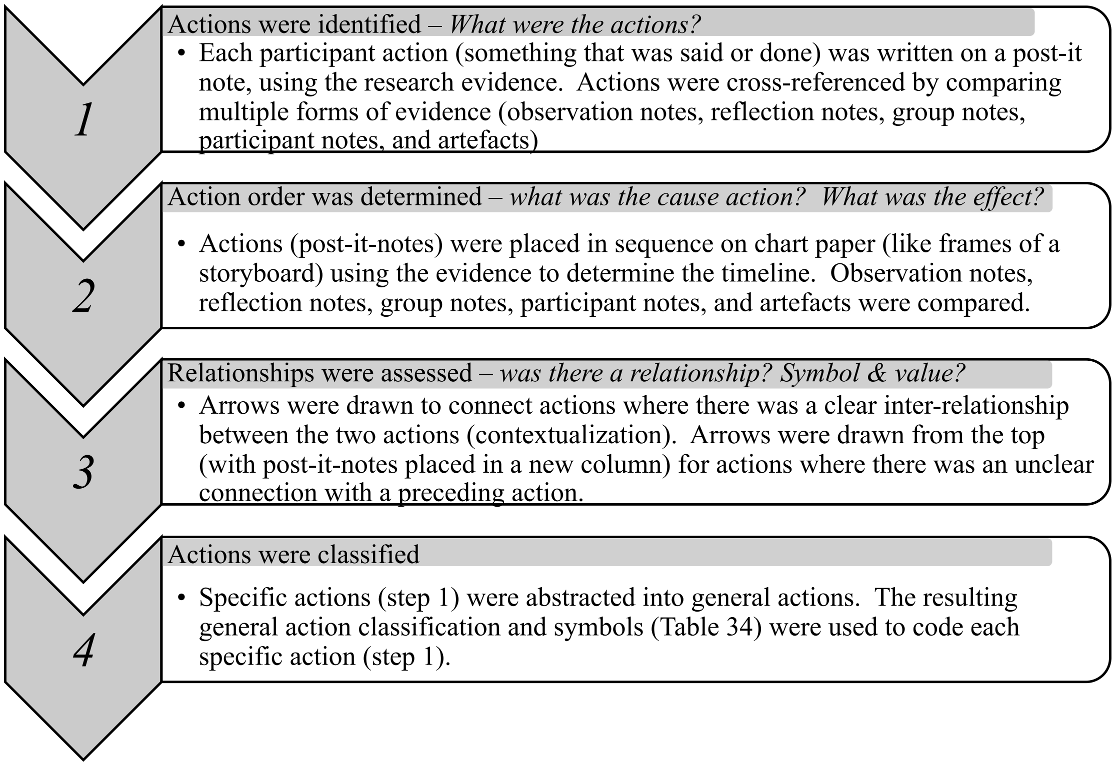


Figure 58: Coding process for the co-design event data

Actions found in the research evidence are organized by themes as general actions in Table 34.

Symbol	General action classification
✔	Concept idea (C)
!	Problem with an idea (P)
?	Question/enquiry about an idea (E)
✔	Need that an idea must address (Nd)
*	Opportunity that an idea presents (O)
✔	Detail idea (Dl)

Table 34: Classification of general actions in the co-design study

Examples for each of the general actions in Table 34 are provided below from four strings of inter-connected actions. The examples are synthesized into definitions.

String	Concept idea
1	• What if we rotated the table?
2	• Create more room by moving around a nearby work station, dividing the two work areas
3	• N/a
4	• Grid on the table to organize components for a quality check

Table 35: Concept action coding examples

As shown in Table 35, a concept is a general, theoretical, abstract, or uncertain idea that is spoken by a participant. An idea pertains in this case to a possible solution variant expressed in the co-design events.

String	Detail idea
1	• Position and orient the table • Find different components and bring pallets beside the table (position, proximity)
2	• Create a separation barrier with a string and post set-up, similar to when you're waiting in line at a bank
3	• Some people have been writing the # of components to pick on the boxes • Write quantity with tape on the ground • Use chalk or whiteboard marker and then erase it • On the ground because people are looking at the ground when they pick • In front of the pallet • Used a sticky note and wrote the quantity on the sticky note and placed it in front of each pallet
4	• Got the largest component (max size) and used electrical tape to make the grid (dimension) • 6 different spots in the grid because 6 components is typically the max but there are exceptions sometimes • Add sticky notes to each grid space with the quantity (of that component) written on them, placed outside of the grid • Sticky notes will change for each component type • Components stacked in the grid space • Grid on the table only filled with the components for one full final product assembly

Table 36: Detail action coding examples

As shown in Table 36, a detail is a particular, specific, applied, concrete, or certain idea that is either spoken or demonstrated by a participant. It describes the properties of a concept. Generally, a concept idea presupposes a detail idea here, but this is not always the case (e.g. in string 3 when a detailed idea from practice and the prior observation is discussed).

String	Problem with an idea
1	• Balancing work might be a problem • Especially when there is an assembly with a large number of components
2	• This area sometimes has a lot of pallets waiting as well
3	• We throw the boxes out though • But it could get rubbed off
4	• N/a

Table 37: Problem action coding examples

As shown in Table 37, a problem is a statement of concern about how a concept or detail idea could behave in the system.

String	Question/enquiry about an idea
1	• Would both builders be working with equal work? • Would one builder be idle and one very busy?
2	• Would this be ok if there was an audit?
3	• Would it still be visible? • Where should the visual be?
4	• How many grid spaces are needed?

Table 38: Question/enquiry action coding examples

As shown in Table 38, a question/enquiry is a statement of curiosity about how a concept or detail idea could behave in the system. Questions can be related to a problem, opportunity, or need but their phrasing is emotionally neutral, versus concerned (problem), optimistic (opportunity), or insistent (need).

String	Need that an idea must address
1	• There was a past audit and having the areas separate and identified was important
2	• N/a
3	• N/a
4	• Size of each grid space • Because quantities (of components for each final product assembly) change

Table 39: Need action coding examples

As shown in Table 39, a need is a statement of insistence about how a concept or detail must address a requirement in the system and its design.

String	Opportunity that an idea presents
1	• More room for components on one side • Double check with respect to quality possible
2	• N/A
3	• N/A
4	• This way the grid could always stay on the table and wouldn't have to be changed for each assembly type

Table 40: Opportunity action coding examples

As shown in Table 40, an opportunity is a statement of optimism about how a concept or detail idea could behave in the system.

The data from the co-design events (PD1&2 and PD3) were coded with the aforementioned considerations and then translated into corresponding adjacency matrices, **A**.

7.1.2.2 FCM adjacency matrices, plots, and analysis

In total, three adjacency matrices were formed in this study – one from the first co-design event ($\mathbf{A}_{1\&2}$), one from the second co-design event ($\mathbf{A}_3$), and an aggregate of the two (A_{total}). Each adjacency matrix is composed from causes (rows), effects (columns), and corresponding linkage values from the coding. Each adjacency matrix is then plotted as a di-graph with cause and effect actions (nodes) and linkages (vectors), known as the fuzzy cognitive map.

The three fuzzy cognitive maps are analyzed in terms of their structure. For each node, the in-degree and out-degree are calculated – the number of linkages that respectively enter or exit the node, as indicated by the direction of the linkage vector relative to the node. These calculations are used to classify each node as a variable type (receiver, transmitter, or ordinary). Nodes with only an in-degree are classified as receiver variables, or overall effects. Nodes with only an out-degree are classified as transmitter variables, or overall causes. Nodes with both an in-degree and out-degree are classified as ordinary variables.

The out-degree (od) for each variable is calculated in Equation 12 (Özesmi and Özesmi, 2004, p. 51) by the row sum of absolute values in the adjacency matrix. The in-degree (id) for each variable is calculated in Equation 13 (Özesmi and Özesmi, 2004, p.

51) by the column sum of absolute values in the adjacency matrix. The centrality (c) for each variable is calculated in Equation 14 (Özesmi and Özesmi, 2004, p. 51) by the summation of the od and id. All three equations were previously shown in §6.2.2.4.

$$od(v_i) = \sum_{k=1}^{N} | a_{ik} | \qquad \text{Equation 12}$$

$$id(v_i) = \sum_{k=1}^{N} | a_{ki} | \qquad \text{Equation 13}$$

$$c(v_i) = od(v_i) + id(v_i) \qquad \text{Equation 14}$$

In addition, the adjacency matrix and fuzzy cognitive map can be analyzed for its complexity. There have been suggestions to analyze complexity based on the total number of receiver variables (Eden et al., 1992) or a receiver to transmitter ratio (Özesmi and Özesmi, 2004). Other considerations include the number of variables (N) in a map and the number of linkages (L, cf. Equation 15, after (Özesmi and Özesmi, 2004) and previously shown in §6.2.2.4).

$$L = \sum_{i=1}^{N} \sum_{j=1}^{N} | a_{ij}| \qquad \text{Equation 15}$$

After calculating these factors, the interconnectivity of a map can be calculated through its density (D, cf. Equation 16 (Özesmi and Özesmi, 2004, p. 51), previously shown in §6.2.2.4). When each node is linked once to every other node with no self-loops, D = 1, indicating a high degree of interconnectivity. Since linkage frequency is coded here, the D values will be higher than for typical FCM plots.

$$D = \frac{L}{N(N-1)} \qquad \text{Equation 16}$$

7.2 Results

The coding from the PD1&2 event resulted in a total of 106 codes, corresponding to the seven different general action classifications (Table 34). Figure 59 illustrates the coding results from the PD1&2 event. Specific codes were discussed in §7.1.2.1 and are also later discussed in §7.5.

Figure 59: Excerpt of coding from PD1&2 event (in the production area, end)

The coding from the PD3 event resulted in a total of 86 codes, with 54 codes corresponding to actions that were taken in the meeting room setting and 32 codes corresponding to actions that were taken in the production area setting. The following Figure 60 illustrates the results of the coding from the PD3 event. Specific codes were discussed in §7.1.2.1 and are also later discussed in §7.5.

Figure 60: Excerpt of coding from PD3 event (in the meeting room)

These coding results were then transferred into adjacency matrices. The coding from the PD1&2 event resulted in the adjacency matrix, $\mathbf{A}_{1\&2}$, outlined in Figure 61. Figure 61 also shows the positioning of the codes in the columns and rows within the matrix (C-concept, O-opportunity, P-problem, E-enquiry/question, Nd-need, and Dl-detail). The coding from the PD3 event resulted in the adjacency matrix, $\mathbf{A}_3$, outlined in Figure 62 with the same code positioning as Figure 61.

$$\begin{array}{cc} Codes & \begin{array}{cccccc} C & O & P & E & Nd & Dl \end{array} \\ \begin{array}{c} C \\ O \\ P \\ E \\ Nd \\ Dl \end{array} & \begin{bmatrix} 0 & 3 & 2 & 2 & 1 & 0 \\ 1 & 1 & 1 & 3 & 0 & 4 \\ 3 & 1 & 6 & 4 & 2 & 4 \\ 4 & 2 & 5 & 11 & 1 & 9 \\ 0 & 0 & 1 & 1 & 0 & 3 \\ 0 & 5 & 4 & 7 & 2 & 15 \end{bmatrix} \end{array}$$

Figure 61: PD1&2 adjacency matrix ($A_{1\&2}$)

$$\begin{bmatrix} 1 & 1 & 0 & 1 & 5 & 0 \\ 0 & 4 & 3 & 1 & 0 & 2 \\ 2 & 1 & 7 & 4 & 2 & 2 \\ 0 & 3 & 0 & 0 & 3 & 6 \\ 1 & 0 & 2 & 1 & 4 & 5 \\ 0 & 4 & 3 & 1 & 2 & 10 \end{bmatrix}$$

Figure 62: PD3 adjacency matrix (A_3)

The combined adjacency matrix for both events, PD1&2 and PD3, was calculated with Equation 17 since the two matrices have the same positioning and redundancy is being measured with these FCMs. The combined adjacency matrix for both events is shown as $\mathbf{A}_{total}$ in Figure 63 with the same code positioning as Figure 61.

$$\boldsymbol{A}_{total} = \boldsymbol{A}_{1\&2} + \boldsymbol{A}_3 \qquad \text{Equation 17}$$

$$\begin{bmatrix} 1 & 4 & 2 & 3 & 6 & 0 \\ 1 & 5 & 4 & 4 & 0 & 6 \\ 5 & 2 & 13 & 8 & 4 & 6 \\ 4 & 5 & 5 & 11 & 4 & 15 \\ 1 & 0 & 3 & 2 & 4 & 8 \\ 0 & 9 & 7 & 8 & 4 & 25 \end{bmatrix}$$

Figure 63: PDtotal adjacency matrix (A_{total})

The fuzzy cognitive map for $\mathbf{A}_{total}$ is plotted in Figure 64. Figure 64 represents each variable or node as a circle. The centrality value for each variable is represented by the diameter of the node/circle. The linkages are represented by vectors/arrows indicate to and from directions.

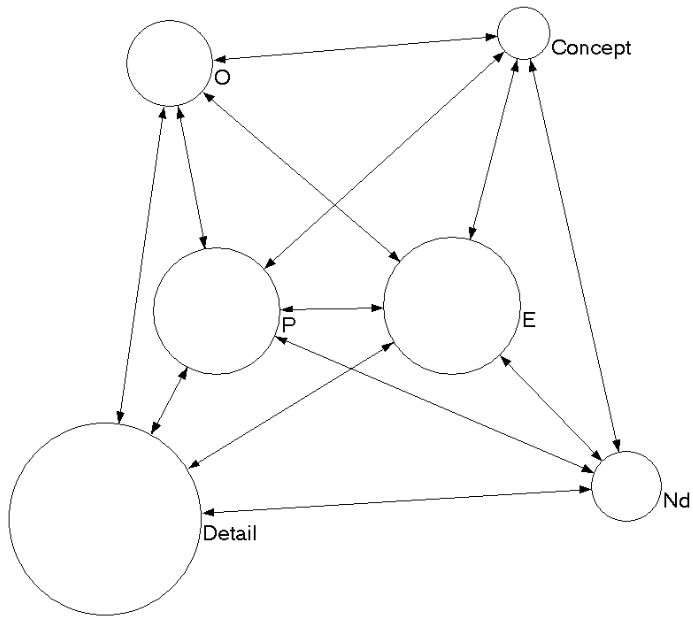


Figure 64: FCM for $\mathbf{A}_{\text{total}}$

Figure 64 illustrates the intricate inter-connectedness of the nodes – opportunities (O), problems (P), enquiries or questions (E), needs (Nd), concepts, and details. This map is analyzed in the subsequent section using the approach and equations outlined in §7.1.2.2.

7.3 Analysis

7.3.1 FCM analysis

7.3.1.1 FCM out-degree, in-degree, and centrality

In the adjacency matrix for the PD1&2 event, Figure 61, there are 6 nodes (N=6). These variables (v_i) corresponded to concept, opportunity (O), problem (P), enquiry or question (E), need (Nd), and detail general actions, where i=1,2,3,4,5,6 respectively. There are 108 linkages (L=108) that connected these nodes, which results in a FCM density of 3.6. The out-degree, in-degree, and centrality for each node, variable v_i, are shown in Table 41.

	Variable v_i					
	Concept	O	P	E	Nd	Detail
$od(v_i)$	8	10	20	32	5	33
$id(v_i)$	8	12	19	28	6	35
$c(v_i)$	16	22	39	60	11	68

Table 41: Out-degree, in-degree, and centrality for variables in the PD1&2 FCM

In the adjacency matrix for the PD3 event, Figure 62, there are 6 nodes (N=6) that corresponded to concept, opportunity (O), problem (P), enquiry or question (E), need (Nd), and detail general actions. There are 81 linkages (L=81), which results in a FCM density of 2.7. The out-degree, in-degree, and centrality for each node, variable v_i, are shown in Table 42.

	Variable v_i					
	Concept	O	P	E	Nd	Detail
$od(v_i)$	8	10	18	12	13	20
$id(v_i)$	4	13	15	8	16	25
$c(v_i)$	12	23	33	20	29	45

Table 42: Out-degree, in-degree, and centrality for variables in the PD3 FCM

In the adjacency matrix for the combined PD1&2 and PD3 events, Figure 63, there are 6 nodes (N=6). These nodes corresponded to concept, opportunity (O), problem (P), enquiry or question (E), need (Nd), and detail. There are 189 linkages (L=189), which results in a FCM density of 6.3. The out-degree, in-degree, and centrality for each node, variable v_i, are shown in Table 43.

	Variable v_i					
	Concept	O	P	E	Nd	Detail
$od(v_i)$	16	20	38	44	18	53
$id(v_i)$	12	25	34	36	22	60
$c(v_i)$	28	45	72	80	40	113

Table 43: Out-degree, in-degree, and centrality for variables in the PDtotal FCM

The values in Table 43 are utilized for further analysis in the subsequent sections. The in-degree (id) and out-degree (od) are further analyzed to classify the variable types (§7.3.1.2). The centrality (c) values are used to create a visual comparison of centrality across the different variables (§7.3.1.3). Finally, the in-degree and out-degree for each variable are further analyzed with the adjacency matrix (Figure 63) to better understand the inter-relationships between variables (linkages) in §7.3.1.4.

7.3.1.2 Classifying the FCM variables as receiver, transmitter, or ordinary

Based on the out-degree and in-degree calculations for the PD1&2 FCM (Table 41), the PD3 FCM (Table 42), and the PDtotal FCM (Table 43) each node (general action) is categorized as a variable type. A node with only an in-degree is categorized as a receiver variable. A node with only an out-degree is categorized as a transmitter variable. A node with both an in-degree and out-degree is categorized as an ordinary variable. In each FCM, the concept, opportunity (O), problem (P), enquiry or question (E), need (Nd), and detail variables have both in-degrees and out-degrees, and are therefore all classified as ordinary variables. In other words, none of the general actions are classified as transmitter or receiver variables; there are no respective overall causes or effects. These results also show that there is no primary direction, i.e. the participants' actions are non-linear; however, this does not mean that the participants' actions are chaotic. The structure of the participants' actions is further studied by analyzing centrality and linkages.

7.3.1.3 Centrality visual analysis

The centrality results for each variable in the PDtotal FCM, from Table 43, are combined into a visual analysis as shown in Figure 65. The variable (general action) with the highest centrality is positioned in the middle with the other variables orbiting in concentric circles. A scale from 0 to the maximum centrality (from Table 43) is created to position the variables. The six general actions (variables) are abbreviated with C (concept), O (opportunity), P (problem), E (enquiry or question), Nd (need), and Dl (detail).

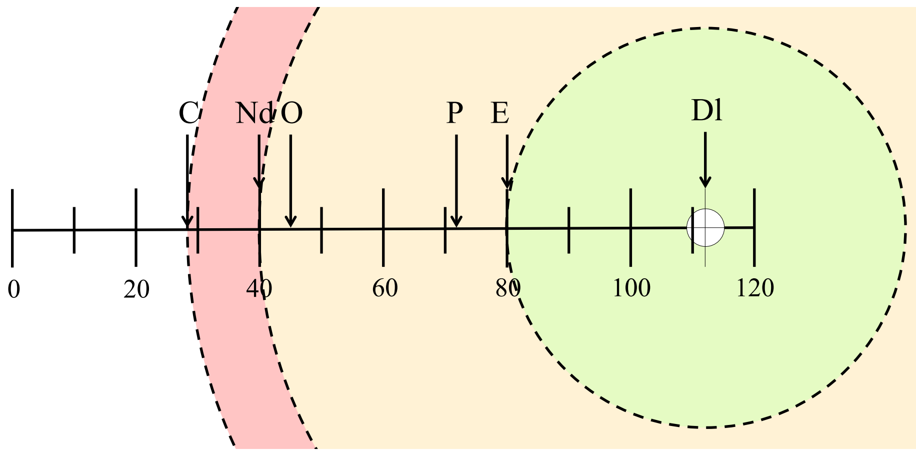


Figure 65: Variable centrality in the PDtotal FCM

The visual analysis of centrality, Figure 65, positions detail in the center with concept positioned in the outermost position or orbit. While there is no overall cause or effect (no transmitter or receiver variables) in the general actions, Figure 65 illustrates that detail is a central aim. The position of detail as innermost is consistent in each of the FCMs (PD1&2, PD3, and PDtotal). The position of concept as outermost is consistent in the PD3 and PDtotal FCMs. In the PD1&2 FCM, c(need) < c(concept), positioning need slightly (5 centrality values) outside of concept, whereby concepts play a more inner role at the beginning of ideation with needs playing a more outer role.

The organization of the concept and detail variables as outermost and innermost is also supported by the comparative in-degree and out-degree calculations in the FCMs. In all three FCMs, id(detail) > od(detail), whereby participant actions moved more towards detail than away from it. In PD3 and PDtotal, od(concept) > id(concept), whereby participant actions moved away from concepts more than towards them. In PD1&2, od(concept) = id(concept), whereby concept ideation played a more predominate role in earlier versus latter events consistent with the centrality results and analysis for concept.

The middle variables in Figure 65, shuffle in position relative to one another in terms of their centrality. In PD1&2, c(needs) < c(opportunities) < c(problems) <c(enquiries). In PD3, c(enquiries) < c(opportunities) < c(needs) < c(problems). In other words, needs and problems became more central moving from the PD1&2 event to the

PD3 event, while enquiries/questions became less central and the position of opportunities remained consistent. In PDtotal, c(needs) < c(opportunities) < c(problems) < c(enquiries).

These analyses show an overall structure of concepts positioned outermost, detail positioned innermost, and opportunities, problems, needs, and enquiries/questions positioned between. The total adjacency matrix ($\mathbf{A}_{total}$) also supports these results. $\mathbf{A}_{total}$ captures all of the linkages between variables (a_{ij}) in both of the co-design events, where i,j=1 for concept and i,j=6 for detail. The a_{ij} values for a_{16} and a_{61} are 0, which shows that there are no direct linkages between detail and concept. The analysis of centrality, in-degree versus out-degree, and absent linkages corroborate in positioning OPEN actions in-between concept and detail actions (OPEN – opportunities, problems, enquiries/questions, and needs). The positioning of the OPEN variables is further analyzed in §7.3.2 and is discussed in §7.5. How the nodes affect one another is analyzed in more detail in the following sections.

7.3.1.4 Analyzing linkages

Analyzing linkages related to the concept variable

The actions/variables (circles) and their linkages (vectors) that lead into, and out of, the concept variable are inspected here more thoroughly. The variables that lead to the concept, and their linkage values, are identified in the concept column of the adjacency matrix (a_{i1}). The variables that the concept leads to, and their linkage values, are identified in the concept row of the adjacency matrix (a_{1j}). For an overview across both co-design events (PDtotal), $\mathbf{A}_{total}$ is used. This analysis is shown in Figure 66 (note: all of the circles representing actions are the same size and do not represent centrality as in Figure 64).

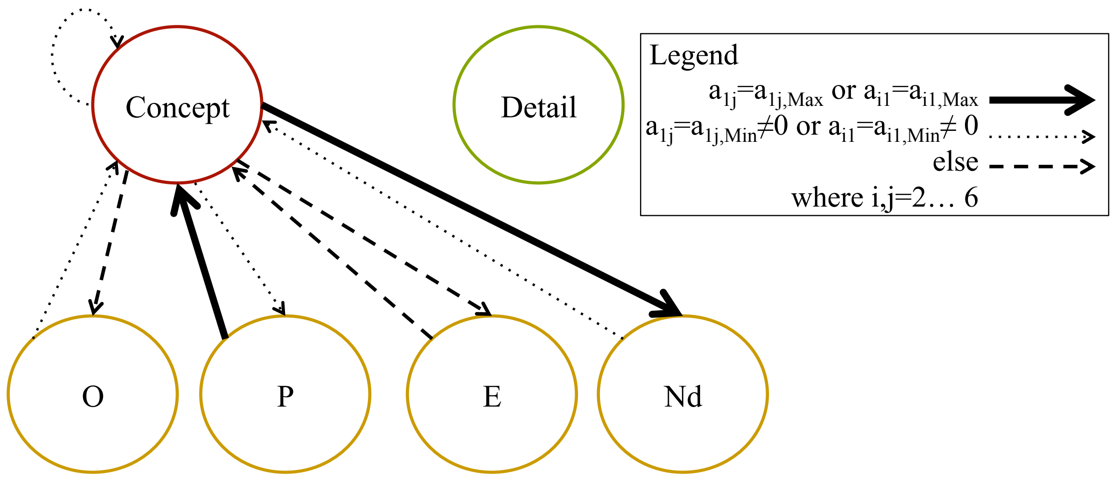


Figure 66: PDtotal FCM – detailed view of the concept variable and its linkages

As shown by the linkage vectors, arrows in Figure 66, the concept variable interacts with opportunities (O), problems (P), questions/enquiries (E), and needs (Nd). Problems most often lead to the concept variable. The concept variable most often leads to needs. Questions play a role in both leading into and out of concepts.

Analyzing linkages related to the detail variable

The actions/variables (circles) and their linkages (vectors) that lead into, and out of, the detail variable are inspected more thoroughly. The variables that lead to the detail, and their linkage values, are identified in the detail column of the adjacency matrix (a_{i6}). The variables that the detail leads to, and their linkage values, are identified in the detail row of the adjacency matrix (a_{6j}). For an overview across both PD events (PDtotal), $\mathbf{A}_{total}$ is used. This analysis is shown in Figure 67 (note: all of the circles representing actions are the same size and do not represent centrality as in Figure 64).

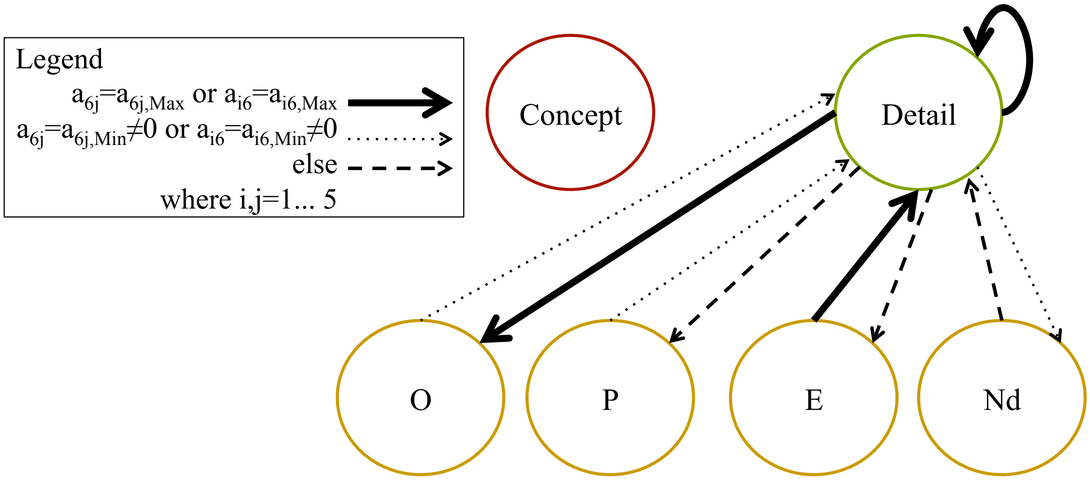


Figure 67: PDtotal FCM - detailed view of the detail variable and its linkages

As shown by the linkage vectors, arrows in Figure 67, the detail variable interacts with opportunities (O), problems (P), questions/enquiries (E), and needs (Nd). Question/enquiries most often lead to the detail variable. The detail variable most often leads to opportunities.

Analyzing linkages related to the OPEN variables

The linkage interactions between the OPEN variables (opportunities, problems, questions/enquiries, and needs) are inspected here more thoroughly. The linkage values in the rows and columns corresponding to these variables in the adjacency matrix are identified. For an overview across both PD events (PDtotal), $\mathbf{A}_{total}$ is used. This analysis is shown in Figure 68 (note: all of the circles representing actions are the same size and do not represent centrality as in Figure 64).

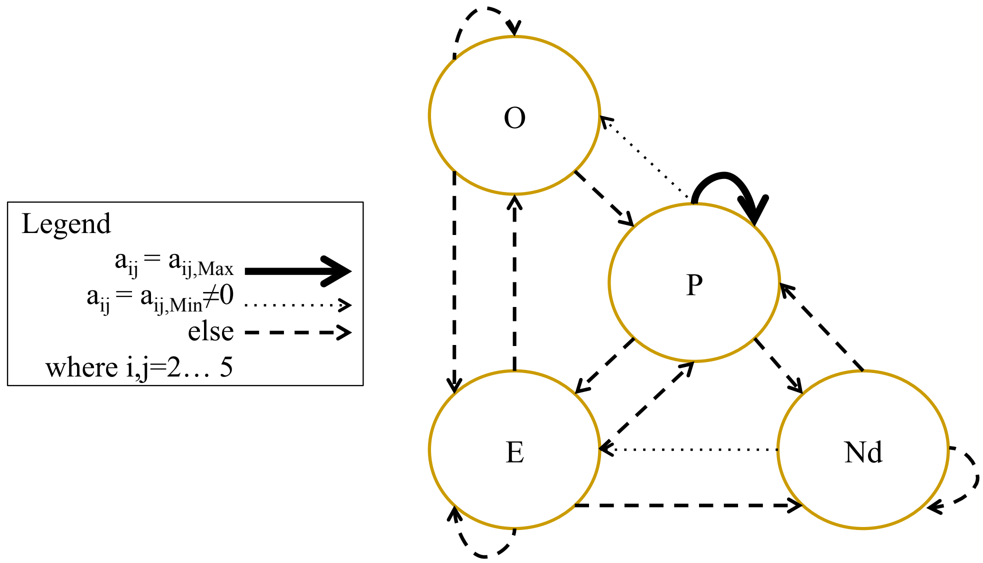


Figure 68: PDtotal FCM - detailed view of the OPEN variables and their linkages

As shown by the linkage vectors, arrows in Figure 68, the most frequently occurring linkage for the OPEN variables is the problem self-loop. The least frequently occurring linkages are from needs to questions and from problems to opportunities. The remaining ten linkages are present amongst all of the OPEN nodes except from opportunities to needs and vice versa, which may represent a polarity between possibility and necessity. This analysis shows that the participants moved between these OPEN variables with balanced linkages between them. To inquire further into the role of the OPEN variables, a more detailed look at their relationship with one another and with the concept and detail variables is explored in the next section.

7.3.2 Visualizing action occurrence with linkages and time

To visualize how the occurrences of the OPEN variables interact amongst themselves and with the concept and detail variables, the following technique of time-plotted variable (action) and linkage visualization is developed. Several visualization ideas are combined. Lines are drawn to represent the general actions, with specific instances of those general actions plotted as circles (similar to the lines on sheet music and notes). The order of the lines is determined by the variable centrality values, per

Figure 65. Arrows are drawn to and from the circles to represent the inter-relationships between actions (similar to precedence diagrams). The x-axis is drawn to represent time, to plot the specific actions as incidences across time (similar to a control chart). The result for the time-plotted variable (action) and linkage visualization from the beginning of the PD1 event is illustrated in Figure 69.

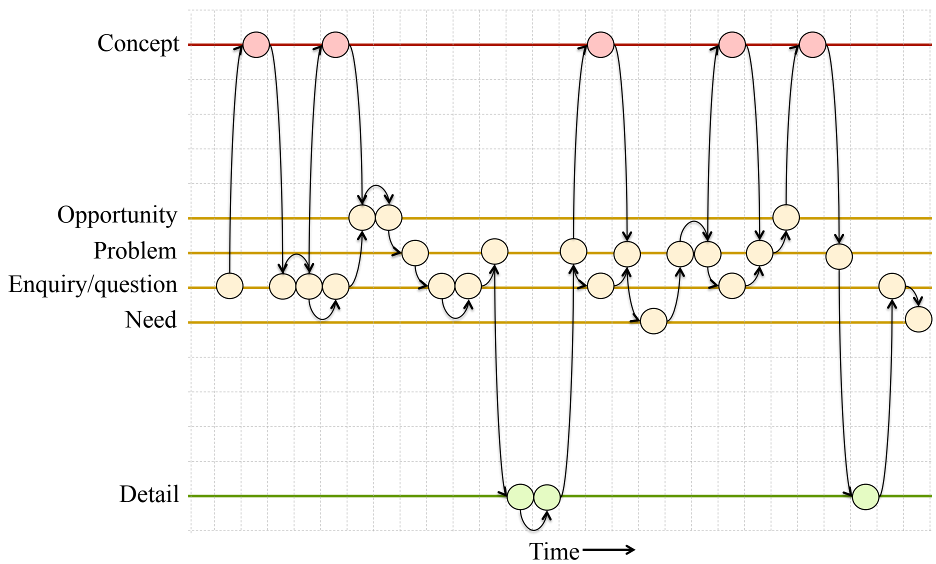


Figure 69: PD1&2 time-plotted variable and linkage visualization (beginning, in production area)

As Figure 69 shows, at the beginning of the PD1&2 event, five of the nine concepts in this event occurr within the first quarter (within the first 26 of 106 actions). This finding suggests that concept generation plays a more critical role early in the co-design event. This is corroborated by other findings, such as the in-degree, out-degree, and centrality analyses in §7.3.1.3, where od(concept) = id(concept) for the PD1&2 event but od(concept) > id(concept) for PD3 and PD total. Also in Figure 69, questions and concept co-occur three times. In all of the coding, assigning two codes for one action was avoided as much as possible; the only time this occurs is with questions and concepts (6 times total) and questions and details (twice). This finding may suggest that questions are very closely related to ideation.

The result for the time-plotted variable (action) and linkage visualization from the middle of the PD3 event is illustrated in Figure 70. If the same action recurred it was represented with a Greek symbol inside the specific action circle.

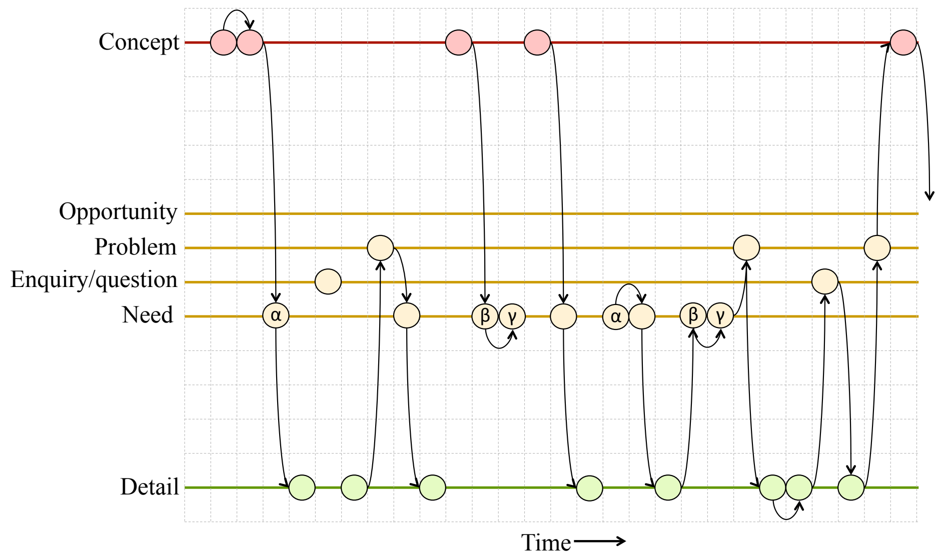


Figure 70: PD3 time-plotted variable and linkage visualization (midpoint, beginning in meeting room)

The coding in Figure 70 represents the midpoint of the second co-design event, where participants were reflecting on the re-designed layout and process that they further co-designed in the first half of the event. At this point in the event, participants went around the table sharing their answers to the question, "What is important to consider in the training design?" As Figure 70 shows, participant actions were not as inter-related in the beginning, but as time went on participants began to refer back to previous actions (e.g. needs in Figure 70, and the strings of actions inter-connected by arrows became longer). This shows how participants share common actions and build on the previous actions of their fellow participants in collective creativity.

7.4 The participants' action model of OPEN collective creativity

By combining the analyses in §7.3, the participants' action model of collective creativity emerges as shown in Figure 71.

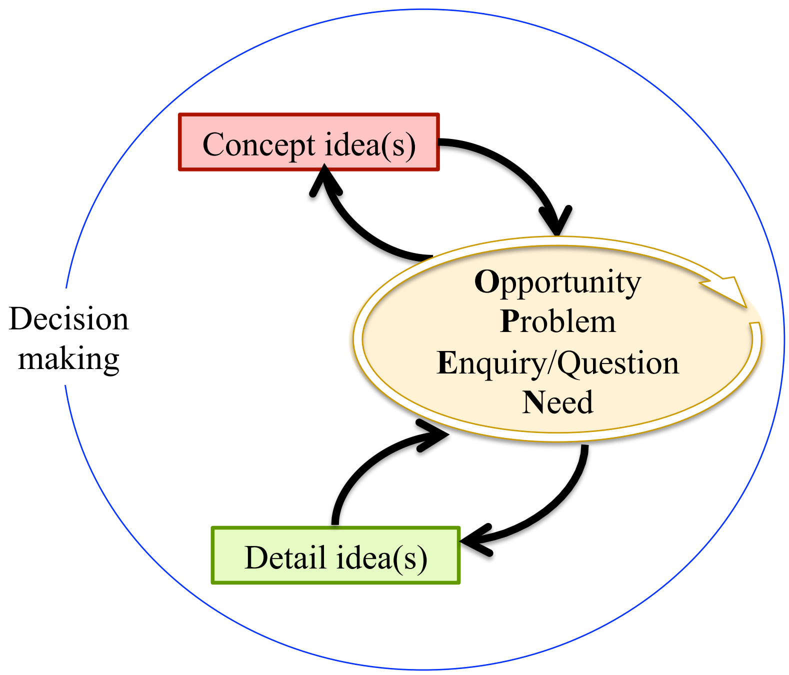


Figure 71: The participants' action model of OPEN collective creativity

The participants' action model in Figure 71 is named OPEN collective creativity from the acronym of the grouped middle variables (Opportunity, Problem, Enquiry/question, and Need). The OPEN acronym is also appropriate as it relates to inclusivity embodied in co-creativity, co-design, and mutual learning. The OPEN term can also serve as a pneumonic device for the central actions of the participants' model, highlighting its shape. The features of the participants' action model are the focus of the discussion.

7.5 Discussion

This discussion first addresses the first research question in this chapter: How do participants take action to co-design solution variants in STS re-design? The participants' action model of OPEN collective creativity, Figure 71, answers this question along with the subsequent discussion of its features, including its non-linearity; its emphasis on asking questions and ability to address conflict and challenge constraints; and its operationalization of human value and potential. The participants' action model of collective creativity and its features are then compared with brainstorming to answer the second research question: How does the model of participant action(s) in collective creativity (in co-designing solution variants in STS re-design) compare with brainstorming?

The OPEN collective creativity model: Non-linearity

The participants' action model of collective creativity focuses on six general actions: stating a concept idea, problem, question/enquiry, need, and opportunity as well as stating or demonstrating a detail idea. All are defined in §7.1.2.1 and are organized with non-linearity, as illustrated in Figure 71. The non-linearity is determined by the classification of the general actions as ordinary variables (§7.3.1.2), based on each general action having both in-degree and out-degree (§7.3.1.1). As a result, multiple analyses in this research reveal a non-linear shape of collective creativity in the participants' co-design action. The meaning of this non-linearity can be understood further in relation to (1) the position of the OPEN actions, and (2) the position of the concept and detail ideas.

(1) Non-linearity and the position of the OPEN actions

Opportunities, problems, enquiries/questions, and needs (OPEN) are positioned between concept ideas and detail ideas in the participants' action model of collective creativity. This is corroborated by evidence of centrality (§7.3.1.3), linkage interactions (§7.3.1.4), and the occurrence of actions across time (§7.3.2). To demonstrate what the position of the OPEN actions means within the non-linear model of collective creativity, a coding excerpt is provided. The following is an excerpt from a sequence of inter-related participant actions, which occurred in the middle of the first co-design event in response to the question: how will the components be picked?

- Some people have been writing the number of components to pick on the boxes (detail)
- We throw the boxes out though (problem)
- Write quantity with tape on the ground (detail)
- Or use chalk or whiteboard marker and then erase it (detail)
- But it could get rubbed off (problem)
- Would it still be visible? (question)
- Where should the visual be? (question)
- On the ground because people are looking at the ground when they pick (detail)

- In front of the pallet (detail)…

This excerpt illustrates that problems and questions are asked by participants to see if the idea will "work" – will the idea create problems that need to be solved? Does the idea present questions that need to be answered? The OPEN actions are a response to an idea (concept or detail) and, likewise, any subsequent related idea(s) respond(s) to them.

When participants use problems, questions, opportunities, or needs to respond to an idea, they are relating the idea (concept or detail) to their understanding of the behaviour of the system as a form of assessment – via a participant concern, curiosity, optimism, or insistence respectively (as defined in §7.1.2.1). Accordingly, the participants embody their assessment affectively, a strictly human quality. Their assessment also contextualizes their ideas using their intimate knowledge of the system behaviour, which they gained by operating the system within it (they are part of the system behaviour). In doing so, the participants are integrating new ideas with the existing design (re-design synthesis and establishing that the re-design "applies to us"); in doing so, they also demonstrate how they can play a critical role in the re-design of the socio-technical system (assembly production system archetype).

In their assessment and contextualization of ideas, the participants express their understanding and meaning of concept ideas and detail ideas within the system, within themselves, and with others (the collective). Participants harness this understanding into action when they respond to problems, questions, opportunities, and needs by offering related concept or detail ideas. This symbiosis is an example of the core view of participation in the participatory design literature:

> *…Any [participant] needs to participate willingly as a way of working both as themselves (respecting their individual and group's/community's genuine interests), with themselves (being concentrated present in order to sense how they feel about an issue, being open towards reflections on their own opinions) as well as for the task and the project (contribution to the achievement of the shared and agreed-upon goals of the design task and design project at hand)* (Robertson and Simonsen, 2013, p. 5).

In summary, the position of OPEN actions in the participants' non-linear model of collective creativity reflects the participants' assessment and contextualization of concept and detail ideas and an expression of the meaning of these ideas within the system, within a participant, and between participants (collective).

(2) Non-linearity and the position of concept and detail ideas

The position of the concept idea and detail idea being separated and connected only by the OPEN actions in the participants' model of collective creativity is corroborated by evidence of centrality (§7.3.1.3), linkage interactions (§7.3.1.4), and the occurrence of actions across time (§7.3.2). This means that a concept idea can be assessed and contextualized into a detailed idea. And in reverse, a detailed idea can be assessed and contextualized into a new concept (abstracted). An example of the latter occurred when there were multiple issues (contextualization and assessment) with a set of detailed ideas, so the assessment led to a new concept idea rather than further detailed ideas. This feature of the participants' model of collective creativity -- to support making an abstract idea concrete and making a concrete idea abstract -- is a significant strength of the model, which is dependent upon the participants' assessment and contextualization.

The OPEN collective creativity model: An emphasis on asking questions, addressing conflict, and challenging constraints

Questions occur more than any other OPEN action in the participants' model of collective creativity (in Table 43 the centrality of questions is 80; needs 40; problem 72; and opportunities 45). By combining questions with the other OPEN actions (including problems), the participants demonstrate curiosity and create a dynamic that integrates problem solving with inquiry. In their survey of creative models, Alberti et. al (2007) found that questioning is the beginning of "most representations of the creativity approach" (p.38) while other approaches combine "'finding the problem' and 'finding the idea'" (p.37). The participants' action model of collective creativity synthesizes these perspectives in a central grouping of the OPEN actions.

Questions also play a critical role in managing conflict in the participants' collective creativity model. The following excerpt of coding in Table 44 illustrates that in the OPEN actions (assessment and contextualization of ideas) the participants sometimes disagree on their assessment of an idea, going go back and forth between problems (concern, shaded in black) and opportunities (optimism, shaded in grey) – a conflict. Here, the conflict climaxes at a constraint and problem.

Specific action	General action
Can we build [modules and final assembly] at the same time? [A new, integrated process]	Question Concept
Require two lot numbers	Need
Which would lead to an excess of lot #s Which would lead to running out of lot #s on the system	Problem Problem
Couldn't we work on two work orders at the same time?	Question
We could get rid of the extra packing and unpacking steps	Opportunity
Feedback would be possible because people using the [modules] could tell the people building the [modules] in real time any problems	Opportunity
Those four people could rotate and work together (2 building modules and 2 building assemblies)	Detail
This would allow builders to build an understanding of the other process	Opportunity
And more job rotation	Opportunity
Inventory would get messed up – now it's organized by [modules] and final assemblies, and some [modules] are built off-site	Problem
Would you have re-work?	Question
This would be significantly reduced or eliminated	Opportunity
It's currently difficult to find people to bring the modules [for the final assembly]	Problem
Modules would flow from one process to the next, reducing the need for material handling [no waiting]	Opportunity
It's the responsibility of those workers to bring them so that the process doesn't run out. They should be doing this. There would also be issues in updating the work order (timing of the processes and shifts) There would also be issues including components in the product structure [for the work order]	Problem Problem Problem
The way this is documented in the system, there are software restrictions	Constraint
Doing it the way it is now is a lot of work for us [production]	Problem
Could it be something that's done when there's a certainty quantity? [a new decision-making structure]	Question Concept
Not every time	Need
What if there's a cut-off quantity?	Question
Whatever fits into the production space [existing floor volume]	Detail
It depends on the work order as well	Need
Quality would need to be involved, so we need to include them in this discussion	Need
Ok, we'll talk to them about this offline	

Table 44: Chain of inter-related actions involving a conflict and constraint

The question that follows the last problem in Table 44 synthesizes the debate of the opportunities and problems associated with an idea and identifies a potential "and" concept (an adaptation of the previous idea that takes into consideration the problems and opportunities raised) versus an either/or solution.

Another constraint arose in the second co-design event. "No overtime. We will not be able to get overtime approval" (constraint) that prevents coordinating an overlap on two shifts (need) in order for the lead hands to conduct training demonstrations with new builders (concept). In both of these constraint cases, and as the excerpt in Table 44 illustrates, the constraint was not peripheral to the solution like a boundary or limit; it was integral and became enveloped by the solution-finding actions of the participants. Interestingly, this shows that in collective creativity the constraint doesn't necessarily define the solution space – people do. Accordingly, the participants leaned into the constraints and questioned them in the design process. It is also important to note that in Table 44 the chain of actions aimed at continuing to try to challenge the constraint by expanding the scope of participation to include workers in quality who are situated at another facility. This highlights a critical relationship between the participants and the roles they represent and the ability to challenge constraints in collective creativity.

The OPEN collective creativity model: Operationalizing human value and potential

Participants operationalize human value and potential across the aforementioned features of the participants' OPEN collective creativity model. The participants' OPEN actions are an affective expression that utilizes their intimate knowledge of the system behaviour (gained from their operation of the system within it). Participants express this analysis with one another and synthesize it into new concepts, with concreteness (a detail idea) or abstraction (a concept idea). They debate ideas (conflict) and also form consensus in their synthesized ideas -- collective decision-making. Across all of these aspects, the participants embody Taylor's (2014) creativity duality of "honouring the individual" (p.3) and "plurality of our social existence" (p.12). This operationalization of human value and potential helps us to understand how collective creativity works with the participants' action model and why creativity is a uniquely human endeavour.

The OPEN collective creativity model: Comparison with brainstorming

For conventional group brainstorm, the standard procedure "consists of a number of people (Osborn suggested between six and 10) working together in the same room, seeking ideas to solve a prescribed problem or challenge. The challenge is stated and ideas are recorded one at a time usually on a flip-chart or whiteboard by either a member of the group or by a facilitator" (Byron, 2012, p. 203). In particular, brainstorming emphasizes quantity, deferment of judgment, free-wheeling, and combination (Osborn, 1953).

The co-design experience in this research, and associated participants' action model, is similar to these brainstorming conditions in terms of the group size (7 or 9 participants) and the recording of actions on chart paper. This co-design experience and participants' action model differs, however, in regard to quantity of ideas and judgment. As previously mentioned, the participant actions did not place emphasis on the quantity of ideas, although the participants generated 113 detail ideas and 28 ideas in the two co-design events. In comparison, the participants asked 80 questions and identified 45 opportunities, 72 problems, and 40 needs. In other words, the particpants focused on OPEN actions over 1.5 times more than detail and concept ideas. They emphasized the OPEN variables to assess and contextualize (analyze and vet) the detail and concept ideas. They directly and purposefully engaged judgment, which is contrary to the first rule of brainstorming; at the same time, the participants generated a number of conceptual and detail ideas.

The participants' action model of collective creativity illustrates that judgment does not necessarily hamper ideation; judgment may actually drive ideation. It is an insight that also makes sense relative to the literature on conflict. If collective creativity is a duality of individualism and social plurality, as Taylor (2014) states, then it very much resembles Kilmann and Thomas' (1975) conflict framework that relates cooperativeness (social) and assertiveness (individual) to various conflict styles. Collaboration is indicative of high cooperativeness (social commitment) and high assertiveness (individual commitment). In this sense, collective creativity can be considered a collaborative approach to conflict. This suggests that in collective creativity it isn't necessary to restrict judgment to prevent conflict; it is an opportunity to engage judgment towards ideation and approach the conflict with collaboration.

7.6 Conclusion

How do participants take action to co-design solution variants in STS re-design? To answer this question, participant action data was collected from two co-design events, which were motivated by the emic problem statement and re-design foci (from the emic problem analysis in Chapter 5 and emic system modeling in Chapter 6). Eleven participants in a range of roles and demographics took part in re-designing solution variants for an industrial assembly production system with respect to process, layout, and training with differentiation. This data was coded and analyzed using an adapted form of fuzzy cognitive mapping to form a de facto representation of collective creativity. This investigative approach resulted in a non-linear participant action model of collective creativity. The model consists of six general actions: concept ideas, opportunities, problems, questions, needs, and detail ideas. The OPEN actions (opportunities, problems, enquiries/questions and needs) are positioned between concept ideas and detail ideas.

Participants take action to co-design solution variants for STS re-design in the model of collective creativity as follows. Participants utilize the OPEN actions to assess (analyze) and contextualize ideas for solution variants in relation to their understanding and behaviour of the system (re-design synthesis and ensuring that the re-design "applies to us"). Participants express this analysis with one another and synthesize it into new concepts, with concreteness (a detail idea) or abstraction (a concept idea). They debate ideas (conflict) and also form consensus in their synthesized ideas -- collective decision-making. The participants use questions to integrate inquiry with problem solving and challenge constraints to define their solution space. Through these actions, the participants embody human value and potential. The participants' action model of collective creativity differs from brainstorming by participants directly engaging judgement via OPEN actions.

The solutions that result from the participants' model of collective creativity are assessed (feasible) and contextualized (differentiated – "applies to us"). In this case, the solutions relate to process, layout, and training. These solutions were further detailed by participants in the third co-design event and are shared in Chapter 8. The trustworthiness and validation of this chapter research are evaluated in Chapter 11. The limitations of this chapter research are examined in Chapter 12.

Based on these conclusions, "Collective creativity" is a critical step after "Emic problem analysis" (Figure 39, Chapter 5) and "Emic system modeling" (Figure 55, Chapter 6) in this dissertation's model for re-designing a socio-technical system, summarized systematically with an IDEF0 model in Figure 72. Figure 72 is related to the research questions in the dissertation study as follows. The inputs, mechanisms, and reference models relate to research question 2 (shown in Figure 72 in *Courier font*). The questions, outputs, and constraints relate to research question 3 (shown in Figure 72 in Calibri font).

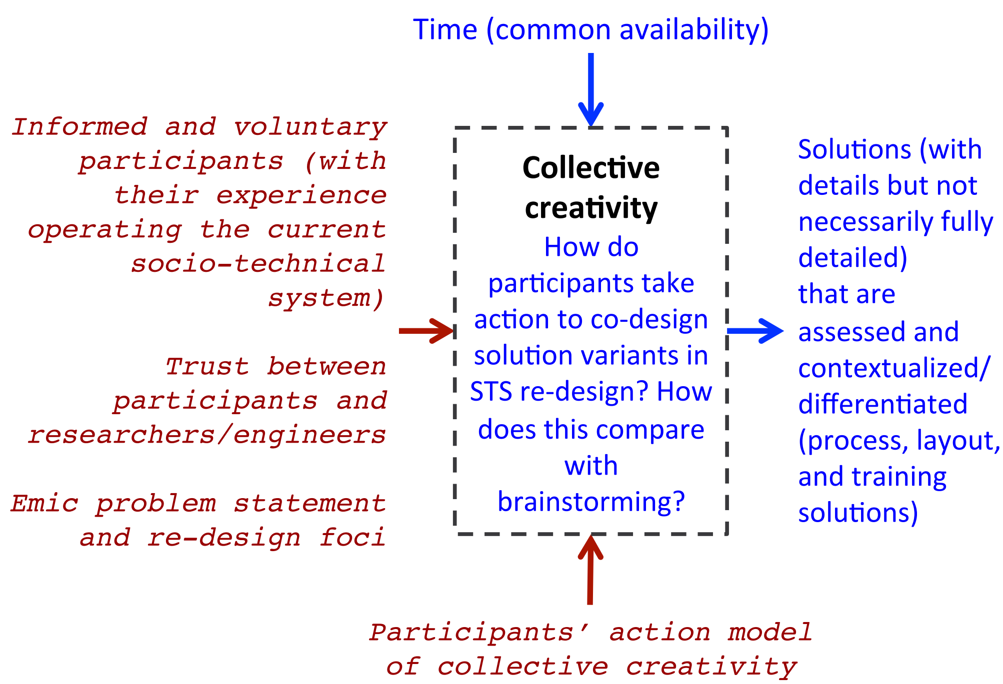


Figure 72: Collective creativity IDEF0

The position of "Collective creativity" (Figure 72) in this dissertation's model for re-designing a socio-technical system is shown in Figure 73.

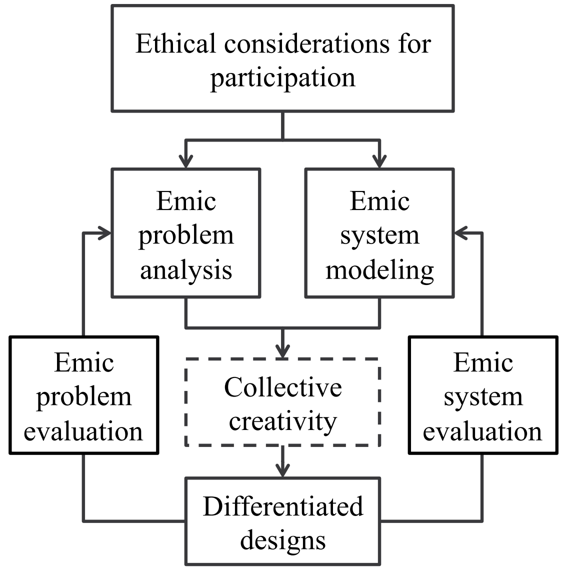


Figure 73: Collective creativity in the developed model for re-designing a socio-technical system

8 Differentiated designs in socio-technical system re-design

In the collective creativity phase, Chapter 7, various process, layout, and training solutions were developed (with details but not necessarily fully detailed) in the first two co-design events. The participants selected several of the solutions to work on further in more detail in several small groups (approximately 3 to 5 people) and continued to work on these solutions in the third co-design event. This chapter shares these detailed solutions (designs) and answers the question: What are the participants' detailed designs for the STS (assembly production system) re-design developed from collective creativity?"

This chapter outlines the major designs that the participants created, broadly grouped as: a re-organized process (with respect to two primary roles of builder and assembler); a re-organized layout; a new quality "double-check" tool; and a new training checklist. These designs are briefly outlined in Table 45 and are further discussed in the subsequent sections; **any identifying information has been removed or covered.**

Design grouping	Detailed aspects of the design grouping
Re-designed process	Two roles for the builders – one picker, one assembler
	Checklist for the different builder tasks (for the picker, assembler, and some shared)
Re-designed layout	Changing the location of the build table (rotating it 90 degrees)
	New layout diagram (designating locations for pallets, etc.)
	Moving the [x] machine and learning how to use it to its full potential
Quality "double-check" system	Grid on the table with locations for the different [assembly] materials
	Labeling system for the grid on the table and pallets (colour-coded, laminated tags with Velcro)
Training checklist	Demonstration of the [assembly] process with the new builders (setting up the example with them)
	Specific people designated as a "[assembly] trainer"
	Sample of the paperwork with different areas highlighted to explain it
	[Assembly] training checklist (including showing how to block and brace, shake test, etc.)

Table 45: The participants' major differentiated designs

The designs in Table 45 are discussed in relation to the description of the assembly components and products, as shared in the industrial context section (§3.4) and repeated here in Table 46 as follows:

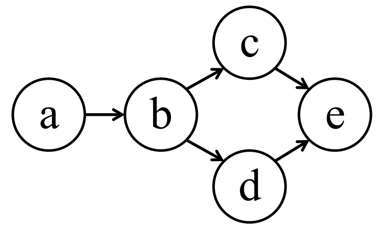
Precedence graph of the component order of assembly	Assembly variant combination descriptions	Component type				
		a	b	c	d	e
	# of sub-types	4	5	37	4	1
	Min # different sub-types	0	1	1	0	1
	Max # different sub-types	1	1	8	1	1
	Min # of components	0	1	24	0	2
	Max # of components	1	1	60	2	15
	Flexible (F) or rigid (R)	F	F	R	F	F

Table 46: Final assembly component variants and precedence (from the pre- and post-observation)

8.1 A re-designed assembly process featuring two builder roles

In the initial assembly production system design, the two builders both picked (selected) components and assembled (combined and positioned) the selected components to build the final assemblies. The participants described this approach as trying to make “everything even” between the two builders so that “everything’s fair.” Performing the same tasks and dividing the components equally was considered the fairest approach. This belief in action created practical challenges towards achieving the equal division and, in turn, the fairness goal.

Dividing the components evenly between the builders proved to be challenging in practice. The pallets of different components and their sub-types were divided between the two builders, at either side of the worktable. One builder worked on one side of the worktable, and the other builder worked on the other side of the worktable. Typically, material handlers or lead hands placed the pallets of the components at either side of the table. For component type C, the number of different sub-types in a final assembly can range from 1 to 8, and the quantity of each sub-type can range significantly, e.g. a final assembly may be comprised with 30 of one sub-type and 6 of another. The other component types typically have a quantity of 1. This situation makes it challenging to “even out” the components on either side of the table. As well, there are often an odd number of different components, further contributing to their uneven division.

With this initial design, there is an inherent conflict between the goals of fairness and the belief of how this fairness can be accomplished. The design of the builder role, the same for both of the builders, consisted of a combination of picking and assembling tasks based on the division of components between them. If the division of the components was fair, then the division of work would be fair. The practical operationalization of this design made dividing the components evenly a challenge, so it was not often possible to realize the desired state of "evenness by components" in order to achieve fairness.

In the co-design activities, the participants created two roles for the builders: one assembler, one picker. On one side of the table is the picker, who selects the C components. On the other side of the table is the assembler, who assembles the components with the platform. As a result, there is no longer the need to divide the C components. There are now two builder roles, picker and assembler, that involve a specialization of tasks. The participants decided to rotate these roles (a form of job rotation) at each break, in order for the builders to not get tired of/from one particular role – to avoid being physically tired (not to perform the same physical work continuously) and also to avoid being mentally tired (not to repeat the same role continuously). In this new design, the builders share the components and divide work based on task specialization. The following is the design note/prototype of the changed roles and process that was created by a group in the second co-design event:

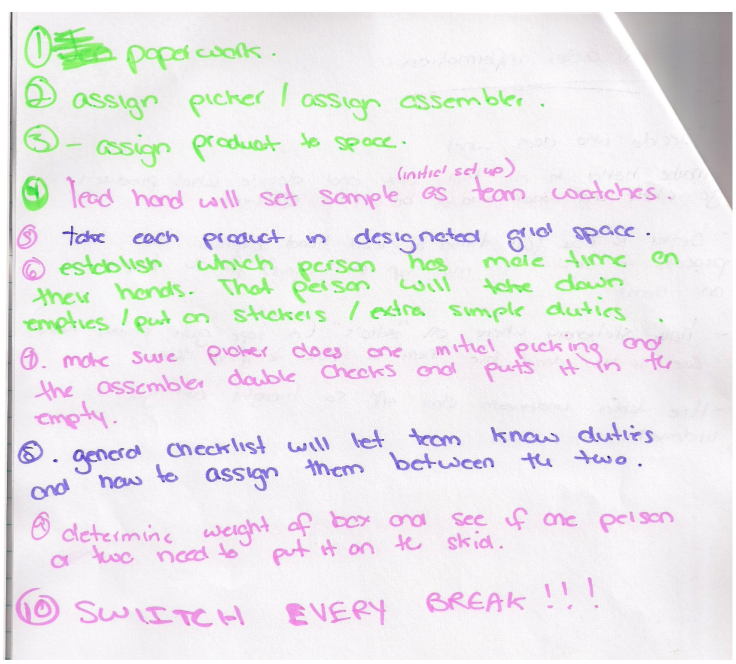


Figure 74: Participant prototype of a description of the new process

In the third co-design event, the participants outlined the re-designed process steps in Figure 74 further by specifying tasks related to the picker and assembler roles as follows in Figure 75.

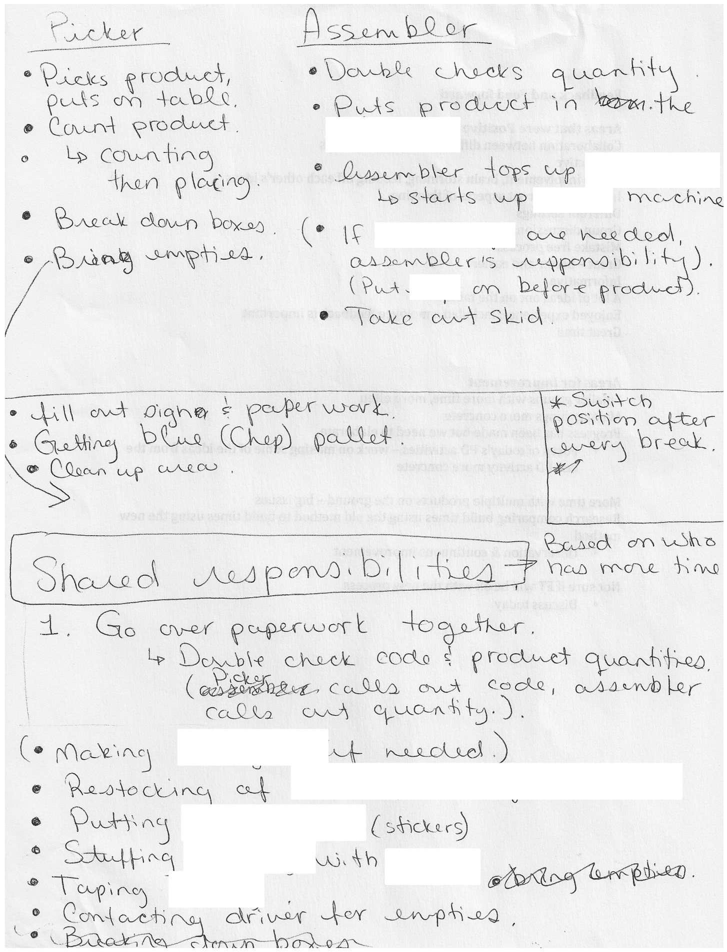


Figure 75: Participant prototype of a checklist of tasks for the new builder assembler and picker roles

The following is a detailed version of the checklist in Figure 75, from a "Performing the Process" section of the new training checklist.

To perform the assembly production process, **the picker** and **the assembler** activities are divided as follows:

The Picker is responsible for these activities:	**The Assembler** is responsible for these activities:
• Opens boxes of component C on pallet • Counts component C on pallet • Picks component C from the boxes on the pallet and puts them on the table in the grid spot for that component C • Breaks down boxes (folds them flat, and places them in the cardboard recycling container) • Brings pallet of component B to be placed beside the table • Fills out signs for the finished skid (Pallet # of #, and tapes it to the pallet) • Fills out paperwork • Gets new pallets when needed to place the boxes of finished assemblies on • Cleans up area	• Double checks quantity of component C in the table grid • Puts product from the table grid into the empty case • Starts machine for component E • Adds component E to the cart • If component A is needed, assembles component A onto component B (before assembling component C with component B) • Takes out skid of finished assemblies from beside the table (places it at the opening of the yellow railing for material handlers to wrap and then put in the warehouse) • Gets component D from the back table and places them under the table

Table 47: Task division for the new picker and assembler builder roles

The picker and **the assembler** also have the following shared responsibilities. After performing the process a few times, **the picker** and **the assembler** decide who is able to do the following activities based on who has more time and what makes the most sense:

- Assembling component D
- Restocking components A and D
- Putting labels on the final assembly
- Assembling component E
- Closing the final assembly
- Contacting driver for more skids of component B and component C
- If the final assembly is heavy, both builders put the final assembly onto the finished skid

Note: **The picker** and **the assembler** switch roles every break, to reduce repetitive motions and support variety of work.

In Figure 75, the participants specified which tasks would be associated with the builder and assembler roles. They also specified shared tasks. The participants designed the shared tasks to be discussed between the two builders and shared the following reasoning for these shared tasks. Depending on the builders, some builders may be able to do certain tasks faster than others, or they may have an interest in one task over another. As well, participants noted that not all builders work at the same pace, for a variety of reasons (e.g. work ethic, interest, motivation, skill, etc.). As a result, the shared responsibilities create flexibility to adjust to these different builder conditions. This organization accounts for the fact that not every builder is the same, and as a result their design reflects corresponding options for flexibility. This is the concept of differentiation – to have a design that supports a common outcome, that is accomplished in more than one way that suits the workers.

The shared responsibility tasks, and overall design for differentiation in the participants' re-designed process and builder roles, are a fascinating alternative to prescriptive technology. As mentioned in the introduction, a prescriptive technology is one that requires compliance (Franklin (1999)). The assembly production line is a typical example of dividing work into smaller and smaller pieces for workers to complete in a sequential fashion, which in turn requires compliance. If one worker does not perform their tasks exactly as specified, all of the workers are affected. The organization that the participants gave to the new builder roles of assembler and picker emphasizes a structure with an overall linearity but not a detailed linear sequence. Interestingly, in the participants' discussion in the second co-design event, one of the participants emphasized how important it is to emphasize the roles and not the task. Since the first event, she had tried the technique with other builders and found that it was easier to explain the process to new builders with roles rather than specific tasks (frequently there are temporary builders). The roles help to describe the process with clear responsibility, which in turn makes understanding the types of tasks easier. This also emphasizes that the intent of the participants' design of the two builder roles (picker and assembler) is not to over prescribe to builders how to accomplish the job. Rather, the intent is to provide a more defined structure within which the builders each have a clear responsibility in regard to their picker and assembler roles and can organize the tasks within their roles, while also making choices about the shared responsibilities in relation to themselves and each other. This is a fascinating solution to providing clarity in the assembly production system without overly prescribing work to the extent that it becomes purely a practice of compliance.

This overall design for differentiation in the participants' re-designed process and builder roles also directly aligns with the third principle of socio-technical systems: Human potential is regarded highly and developed (F. Emery, 1989b). This is described as: "At the simplest level, the third principle would indicate designing-in a degree of multiskilling that would meet the probable arrangements of the section about its tasks. At a more sophisticated level of design, account would be taken of the human potentialities for reasoning, creativity and leadership that might be expected in any group of 8 or 10 human beings. This would mean designing the social system of the small group so that it becomes an instrument for its members – something they largely manage themselves – not vice versa" (F. Emery, 1989b, p. 18). Further, Cherns (1989a) emphasized that the joint optimization of the social and technical utilizes "the adaptability and innovativeness of people in attaining these goals instead of over-determining technically the manner in which these goals should be attained" (p.3). This is exactly what the participants designed in their re-design of the process with the two builder roles of picker and assembler. Each role consists of several tasks (multi-tasking) combined with job rotation, and the shared responsibilities place the builders in a position of reasoning with a small list of decisions to be made. The re-design of the builder roles and process also shows the integration of work and process, another socio-technical systems theory concept – work as a crux of connection between the social and technical aspects of the system and a means to manifest human potential in collective human activity (Trist and Bamforth, 1951, p. 14).

This re-designed process and work has a cascading effect on re-designing the layout, quality measures, and the training.

8.2 A re-designed layout supporting builder roles

In the initial process design, the intent was to divide the components evenly on either side of the table since both of the builders performed picking and assembling tasks. This meant that the layout had to accommodate for this, providing space on either side of the worktable for the pallets of the components. The layout reflected the outcome of the worker attempts to even out the components on either side of the worktable in relation to a fixed product layout. The following is a typical layout, which was taken in the pre-observation and is repeated from §3.4.

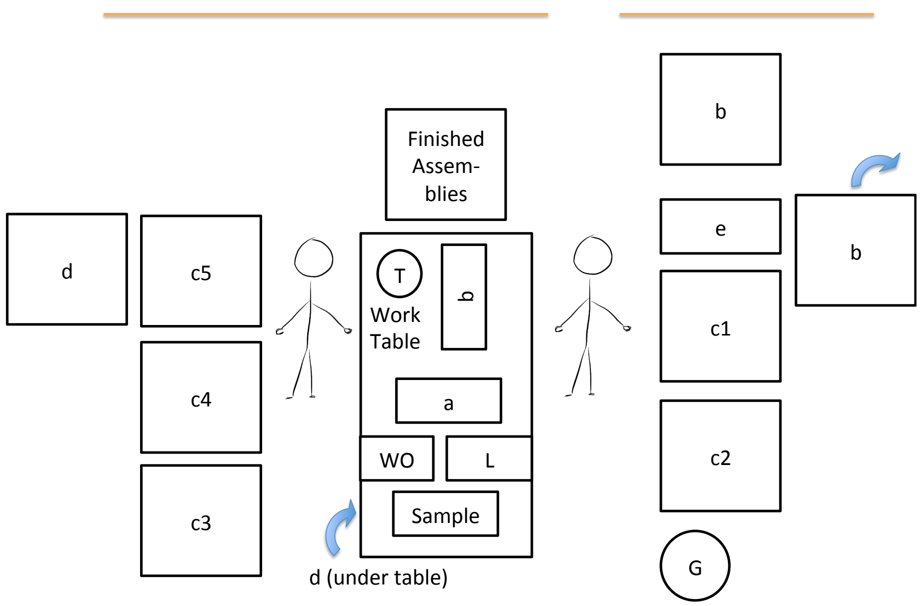


Figure 76: Fixed product layout (from the pre-observation)

In the first co-design event, the participants moved around the pallets, worktable, and other objects in the assembly process space. The following is a rough sketch that was made on chart paper towards the end of this event to capture some of the physical changes that had taken place. The researcher started this drawing and the participants discussed and further drew the drawing, with the finished drawing illustrated in Figure 77.

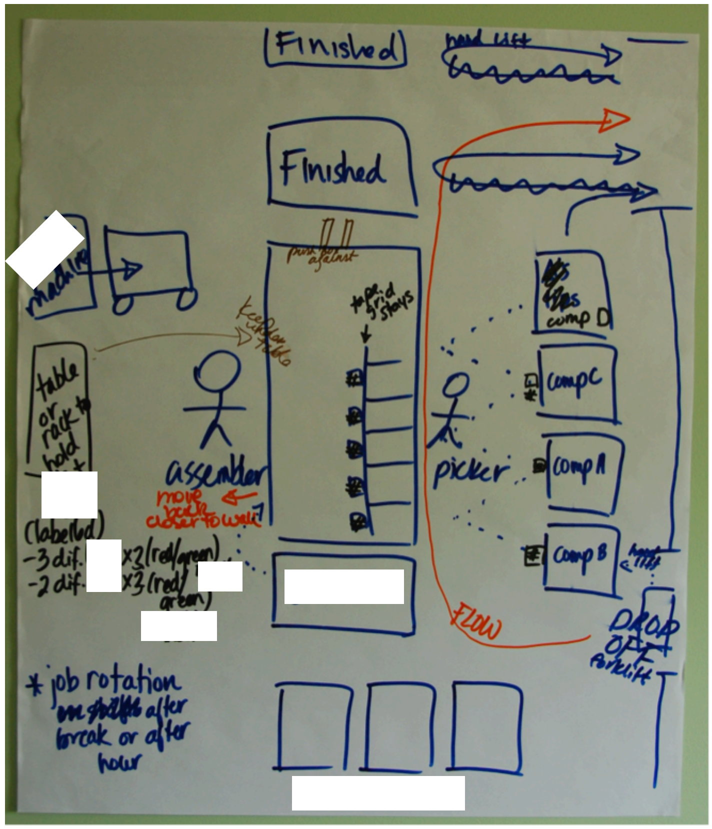


Figure 77: Re-designed layout sketch

In the participants' re-designed layout, the intent is to organize the components in line with the design of the picker and assembler roles of the builders. The platform component remains primarily fixed on the worktable during assembly and the worktable becomes a connection point between two sub-processes. The layout is a combination of a product-process (cellular) layout and a fixed product layout; interestingly, the processes are defined from the roles of the builders as opposed to the roles of a machine (the latter being the position from which cellular layouts are typically defined). In addition to the organization of the re-designed layout in keeping with the builder roles, the participants also rotated the table 90 degrees to change the flow of the materials, re-oriented the machine for component E to place components directly in carts, and created a clearer designation of the component pallets as shown more clearly in the following new layout sketch, as it is described in the new training checklist.

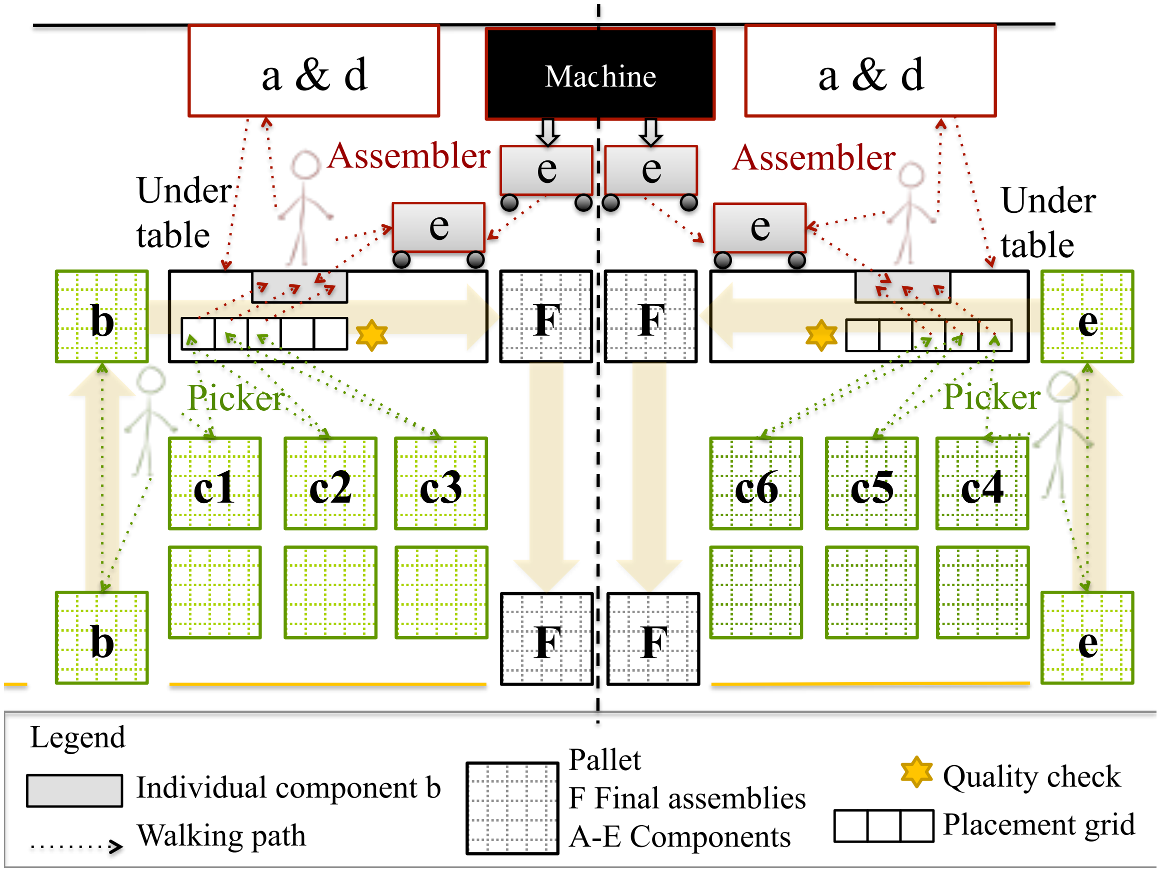


Figure 78: The re-designed layout

As Figure 78 shows, the participants also created a new "quality check" tool on the worktable, which connects both with the new roles of picker and assembler and the new layout. This is explained in more detail in the subsequent section.

8.3 A new quality "double-check" tool

In the initial assembly process and builder roles, each builder picked and assembled their components. Sometimes this led to mis-counts in regard to component type C, which resulted in lengthy inspections of final assemblies to determine where the mis-counts occurred. This quality concern was discussed in the pre-interviews in the emic coding and was a prioritized emic code in the problem analysis.

In response, in the first co-design event the participants created what they call the "double-check," a tool that provides just that – an opportunity to double-check the component quantities for component C. This tool consists of a grid that the participants created on the worktable using electrical tape. The electrical tape enables the participants to create a solution that would remain put but that also could be adapted if the grid needed to be changed. The participants selected the largest component C and sized each grid space to accommodate this largest component. The participants selected 6 grid spaces, because 6 is the typical number of different sub-types of component C in a typical assembly. The intent of this design is for the picker to select the different component C sub-types, then place them in the grid space. The participants decided that multiple quantities would be stacked. The assembler then double-checks this quantity before assembling the component with the platform. This design is illustrated in Figure 79 and Figure 80.

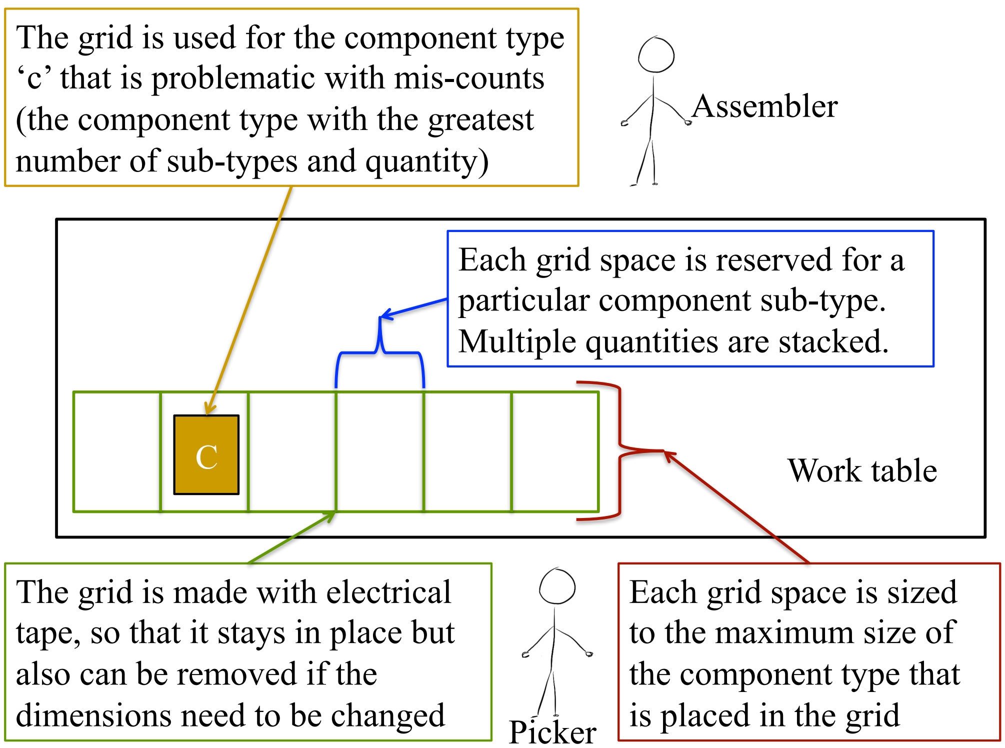


Figure 79: The participants' "double-check" grid

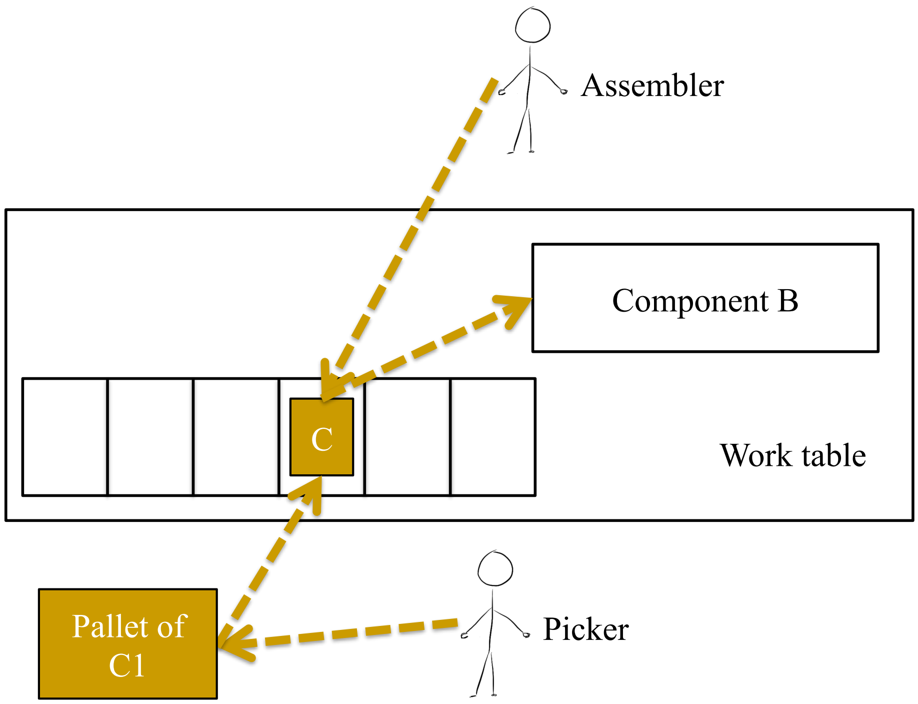


Figure 80: Assembler and picker use of the "double-check" tool

The second part of this "double-check" tool is an accompanying label system to go along with the grid. In the first co-design event, the participants utilized a sticky-note system. A sticky note was placed on each grid space as well as each pallet, indicating the quantity of each component. This allowed the label system to be readily changed for each new final assembly type, which is always changing in an assemble-to-order system (changing the label system at the start of each production run). In the second co-design event, the participants decided to work on this design further to create "a concrete way to identify components on the table and pallets." Participants were concerned that the sticky notes were not robust for the amount of parts moving across the grid. In turn, the participants iterated the design into the following label system in Figure 81 and further illustrated in Figure 82.

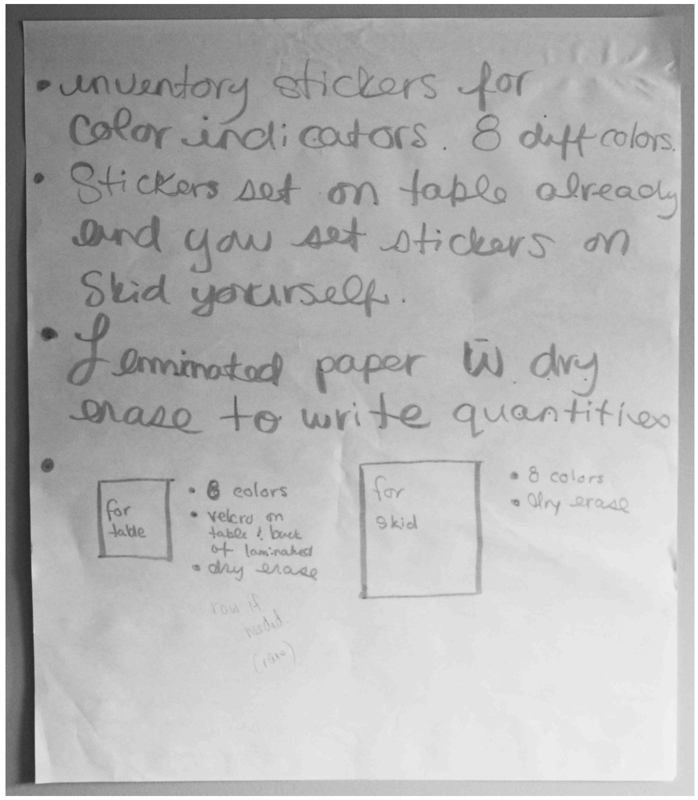


Figure 81: The participants' description of their prototype labeling system for the "double-check" grid

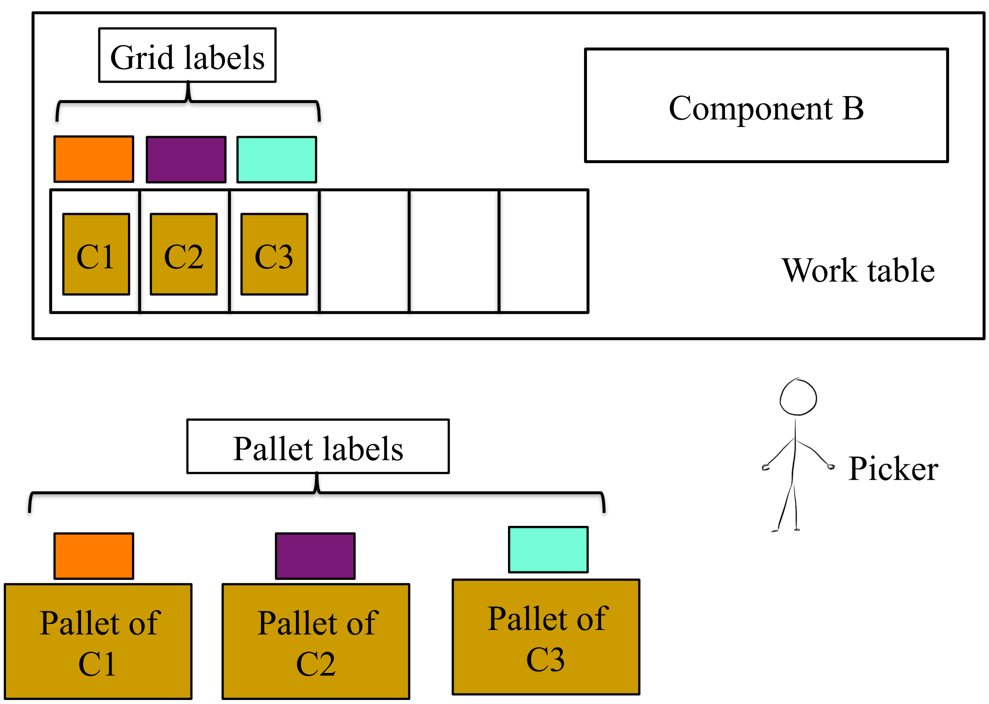


Figure 82: Illustrating the labeling system for the "double-check" tool

Both Figure 81 and Figure 82 illustrate the participants' labeling system that accompanies the grid, which together form the "double-check" tool. Each of the labels is a different colour of construction paper that is laminated for durability. Each component C sub-type is given a different coloured label. Labels are placed on the floor or on the pallets and on the corresponding grid space. The participants determined that the order of the grid should be the same as the order of the pallets on the floor for clarity. The labels are fixed with Velcro onto the grid space and are oriented to face the assembler. The quantity of each component C sub-type is written on the laminated label with dry erase marker, so that it can be erased and re-used for the next assembly production run with the new quantities that are required for the next final assembly type. This double-check tool does not eliminate all mis-counts, nor does it try to control the phenomenon. The aim of the double-check tool is to manage the occurrence of miscounts by helping builders to identify component C sub-type quantities, using visual cues and physical organization. All three of these designs – the re-design process with assembler and picker builder roles, the re-designed layout, and the quality "double-check" tool are incorporated into the new training checklist as follows.

8.4 A new training checklist

In the initial assembly system design, there was not an organized mechanism of training. Builders were trained by other builders or by lead hands. Often, they were instructed what to do after errors had occurred. As a result, the need for builder training was a theme in the emic problem coding and problem analysis. In response, the participants worked on training co-design in the second and third co-design events. The participants outlined the need for the training to be inclusive of a demonstration and with the outline in Figure 83.

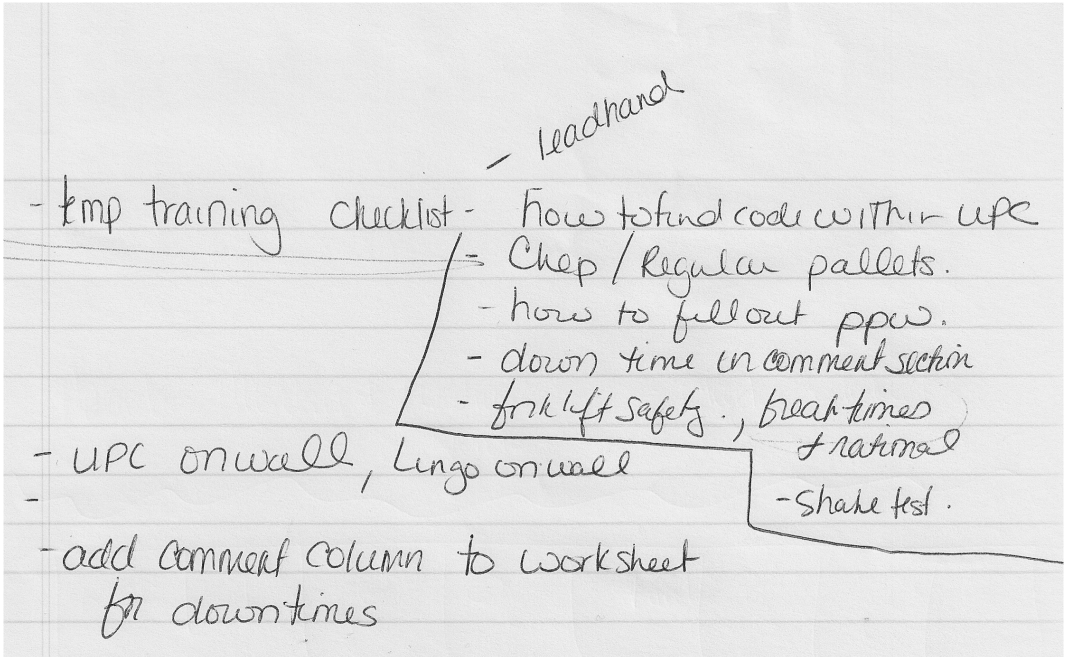


Figure 83: The participants' training checklist outline

This checklist outline was used as a guide to collect the relevant corresponding information as well as information on the previously discussed re-designs. As a result, the checklist for training builders was designed in detail with the structure in Figure 84.

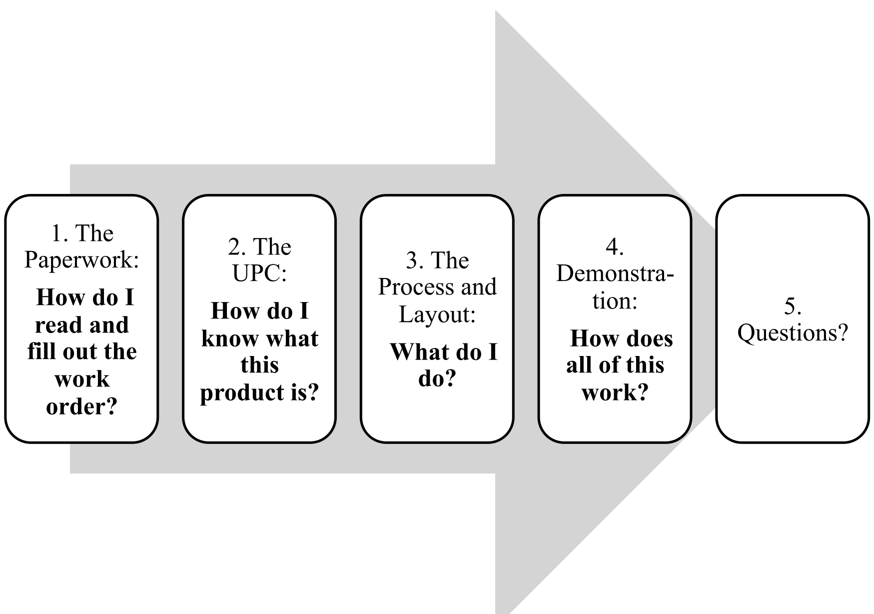


Figure 84: The new training checklist structure

In alignment with Figure 84, the first section provides an example of the work order, highlighting an explanation of the pallet types and how to identify them and an explanation of the various sections of the work order. The second section provides a sample of a UPC code (universal product code), which shows how to identify the different component types in order to identify the different components that are called for on the work order. The third section provides the layout diagram (Figure 78) and the roles and tasks as described in §8.1 (with corresponding colour coding). The third section provides a checklist for the demonstration between the assembly process trainer and the trainee as follows (some information has been changed and removed for confidentiality):

④ Demonstration: How does all of this work?

The trainer (e.g. lead hand) will build one with you. This will remain on the table as an example.

During the demonstration, you will see:

- ☐ How to refer to the work order (e.g. for the quantity of each product)
- ☐ How the activities of the picker and assembler work together
- ☐ How to use the table grid and the importance of the double-check
  - Product is counted twice – once by the picker, and once by the assembler
- ☐
- ☐
- ☐
- ☐ How to use the machine
  - How to set the nachine
  - How to re-set the machine

Figure 85: The new demonstration checklist for training

The final section encourages questions both now and in the future: "If you have any questions, please ask now! If you have questions later, you are encouraged to contact the lead hand at any time with your questions."

This builder training checklist design provides a structure for ensuring that common information that is important as identified by the participants, and that has been misunderstood in the past, is discussed with new builders. It also important to note that the participants emphasize the demonstration aspect of the training, to provide an experience from which the builder can ask questions, which in turn can be addressed by the trainer. This is another example of differentiation. While there is some standard information that's helpful to share, workers who are new to the builder role may have different questions based on their past experience, previous training, skills, knowledge, etc. This type of training is a responsive approach to the builder's needs, promoting dialogue between builders and the trainer. It does not assume that each builder will learn the same; it facilitates several modes of learning (discussion, reading, demonstration, and visual learning), which may be helpful for different builders depending on their personal learning style.

Together, these designs (§8.1 – §8.4) integrate various social and technical aspects -- the re-design foci of process, layout, training, and differentiated designs. The designs incorporate several individual considerations in determining shared builder tasks; providing clarity in the layout; helping to manage errors in quality; and communicating the assembly process through various modes of learning. In turn, these designs speak to human value and potential in combination with differentiation, respecting workers and their differences, and managing the variety that this assemble-to-order production system requires. The designs are highly interconnected, highlighting the mutuality of designs in socio-technical systems and why holistic approaches are needed in re-design in order to understand the meaning of transformation across the system. All of the designs also wholly embody the differentiation design principle – "applies to us" (with "us" being the participants, the socio-technical system operators).

Based on these conclusions, "Differentiated designs" is a critical step after "Collective creativity" (Figure 72, Chapter 7) in this dissertation's model for re-designing a socio-technical system, summarized systematically with an IDEF0 model in Figure 86. Figure 86 is related to the research questions in the dissertation study as follows. The inputs, mechanisms, and reference models relate to research question 2 (shown in Figure 86 in *`Courier font`*). The questions, outputs, and constraints relate to research question 3 (shown in Figure 72 in Calibri font).

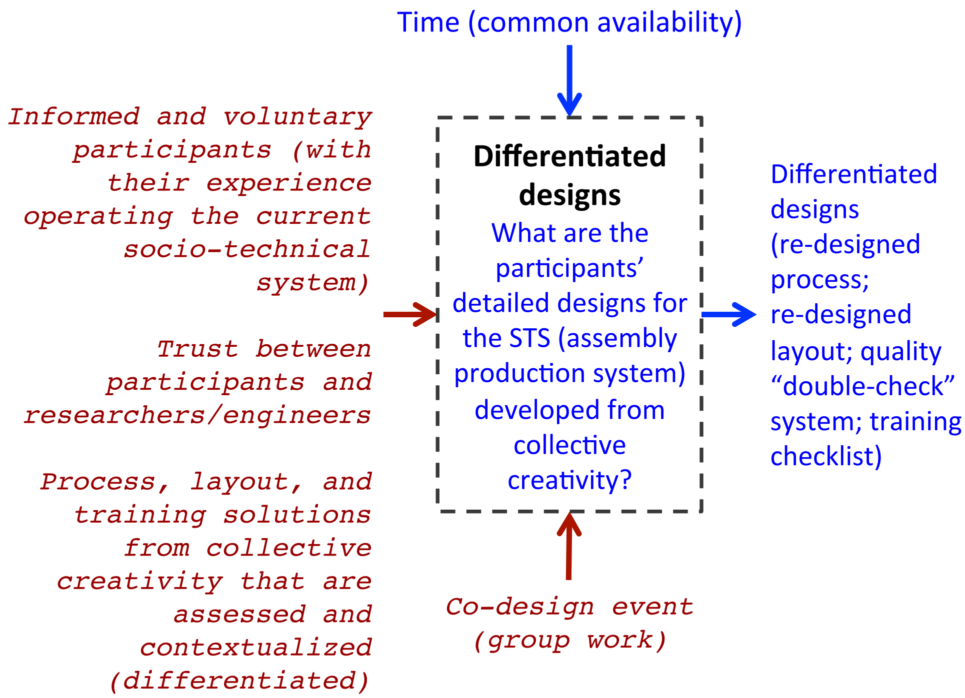


Figure 86: Differentiated designs IDEF0

The position of "Differentiated designs" (Figure 86) in this dissertation's model for re-designing a socio-technical system is shown in Figure 87.

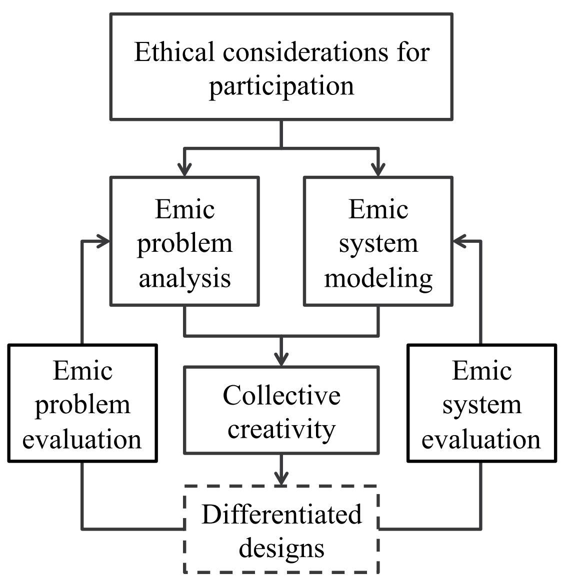


Figure 87: Differentiated designs in the developed model for re-designing a socio-technical system

9 Emic system evaluation in socio-technical system re-design

After establishing differentiated designs (Chapter 8), the next step in developing a participatory approach for re-designing a socio-technical system is to evaluate the designs, comparing the before system model (pre-observation operational model in Chapter 6) with an after system model (post-observation). In this chapter, the differentiated designs §8.1-8.3 are implemented as a design intervention and post-observation data is collected on their use. Evaluation is positioned late in engineering design methodology (Pahl et al., 2007, p. 16) and systems design methodology (Whitten and Bentley, 2007, p. 30). System evaluation has not been explicitly related to STS theory in re-design (Table 5).

In turn, the research in this chapter asks: How can the differentiated designs be evaluated in a before versus after STS model comparison? This chapter investigates this question with an emic (insider/participant) approach, grounding the research in qualitative methodology (§3.2) and further developing the descriptive study II of design research methodology (§3.1, Figure 6). The chapter's research questions are explored *in situ* in the re-design of an assembly production system and socio-technical system archetype. The industrial context and participants are described in §3.4.

Consequently, this chapter sets out to test the post-observation data with the investigative approach that built the observation operational model of the system in Chapter 6 from the pre-observation data. The observation operational model was analyzed with fuzzy cognitive mapping (FCM) in Chapter 6; this chapter shows how the observation operational model and its equations were developed prior to FCM via the investigative approach in §9.1. These equations and their related statistical models are used in this chapter to analyze the pre- and post-observation data. The differentiated designs constitute a shift in the over-arching organizing principles for how people relate to the process and layout, referred to as the working design strategy in this chapter. The pre-observation data reflects the before working design strategy; the post-observation data reflects the after working design strategy (the differentiated designs). The results from the pre- and post-observation are then compared and discussed (§9.2), highlighting a reduction in cycle time in the post-observation (in the use of the differentiated designs).

In this chapter, the primary ideas and sections §9.1 and §9.2 (including tables, figures, equations, and excerpts) are taken from the paper, "A Case Study Measuring the Impact of a Participatory Design Intervention on System Complexity and Cycle Time in an Assemble-to-Order System" (Townsend and Urbanic, 2015). Titles have been changed to align with this dissertation; any wording additions are indicated with square brackets. This conforms to the Elsevier Manufacturing Procedia copyright agreement and clearances in Appendix N.

9.1 The emic system model evaluation investigative process

There is an inherent analytical challenge when assessing a design intervention in an assemble-to-order system because the final products are by nature highly varied, unpredictable, and may not be repeated. Therefore, before and after observations are not directly comparable. Here, the investigative process takes this into account by first creating observation models then using them to predict theoretical direct comparisons. The investigative process is outlined in Table 48. Steps 1-9 relate to the observation calculations and steps 10-11 relate to the theoretical calculations before (B) and after (A) the design intervention. Steps 1-9 are outlined in Figure 88 with steps 10-11 highlighted. Step 12 relates the observation and theoretical calculations.

Step #		Investigative process step description (Data collection and analytical methods)	§ (Results)
B	A		
1	6	Observe the assembly process. Gather data on the assembly product structure, layout, process steps, production phase, and cycle time.	9.2.1
2	7	Test for elementary units in the data that explain variation in the cycle time population using ANOVA (Welch's) and regression.	9.2.1
3	8	Define complexity variables from the relevant elementary units and combine these variables into a complexity ratio (r). Calculate the complexity ratio (r) and mean cycle time ($X\text{-bar}_{CT}$) for each assembly code.	9.2.2
4	9	Plot $X\text{-bar}_{CT}$ vs. r, and then test the correlation with regression.	9.2.3
5	5	Design intervention (participatory design), repeat steps 1-4 for the after (A) observations.	
10	10	Calculate theoretical complexity ratios, before (r_{TB}) and after (r_{TA}), for each assembly code per [Figure 88].	9.2.4
11	11	Using r_{TB} and r_{TA} and the appropriate correlation function (from step 4 or 9, Y=), calculate the theoretical mean cycle time ($X\text{-bar}_{CT,T}$)	9.2.4
12	12	Perform a mean cycle time comparison (before, after) using a paired t-test.	9.2.4

Table 48: The [emic system model evaluation] investigative process (B-before, A-after)

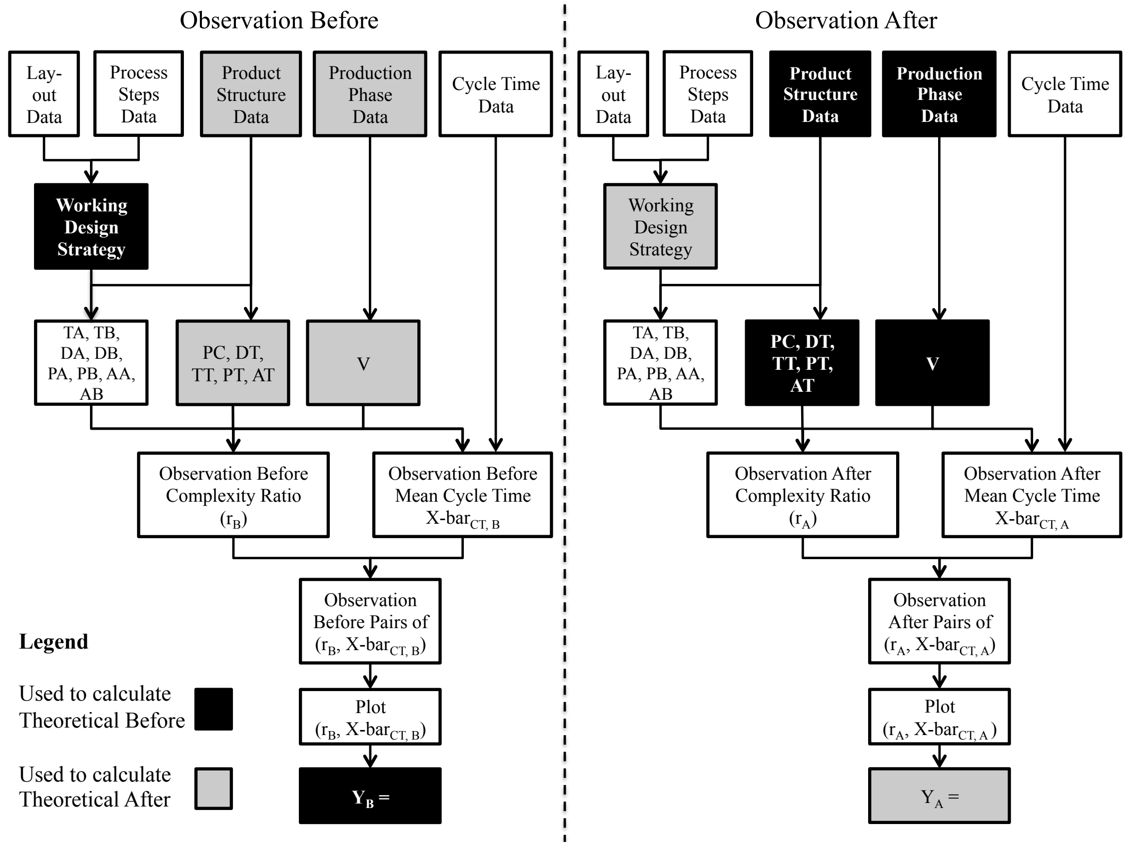


Figure 88: Flow of the observation investigative process steps

9.2 Results and analysis

9.2.1 Observation data and elementary units

The observations are taken before (pre-observation [Chapter 6]) and after (post-observation) the design intervention. Within these phases, the samples are collected at random time intervals. A sample corresponds to one assembly cycle, one cycle time. Random sampling ensures that each elementary unit has an equal chance of being selected. Replacement amongst elementary units takes place, meaning the same combination of elementary units (assembly code, product family, total number of components, number of different components, etc.) can be sampled more than once. This occurs when several observations for a particular production run are gathered. These techniques add robustness to the data collection and subsequent statistical analysis through representativeness and independence amongst sample units. In the pre-observation (before), 226 data samples are analyzed (i.e. 226 assembly cycles) from 10 production runs. In the post-observation (after), 145 data samples are analyzed (i.e. 145 assembly cycles) from 8 production runs.

An exploratory statistical approach is used to detect if the elementary units in the observed data correlate with variation in the cycle time population. The following elementary units are tested. The total number of components (TT) is count data that refers to the number of components in an assembly. The number of assembly tasks (AT) is count data that refers to combining and positioning the selected assembly components. The number of picking tasks (PT) is count data that refers to selecting the components. The assembly code is categorical data that refers to an assembly type identifier. The pallet count is discrete data that refers to the number of finished assemblies that will fit on one pallet (relative size of the finished assembly). The production phase is categorical data that refers to when the observations are taken relative to the start, end, or a full production run. The product family is categorical data that refers to a common assembly platform. The number of different components (DT) is count data that refers to the number of distinct component types in an assembly.

Since the elementary unit groups involve either categorical, discrete, or count data, ANOVA (Analysis of Variance) tests are conducted. For count data that has a range over 10, a regression analysis is also conducted (*3M Six Sigma DMAIC Guide Book*, 2005, p. 38). The null hypothesis (Ho) tests if the means of the groups for a particular elementary unit are statistically equal. The Ho is rejected when the p-value is < α, where α=0.05 for a 95% degree of confidence. For a normality best fit, cycle time transformations can be performed (ReVelle, 2002, p. 329). Here, cycle time data is multiplied by a factor of 1/(archived minimum mean cycle time) for confidentiality then transformed for normality with a Box-Cox transformation ([best fit for] pre-observation) and log-logistic transformation ([best fit for] post-observation); the normal probability plots are tested with a fat pencil test. In addition, groups in the ANOVA are tested where the sample size of each group (n) is > 15 to further build robustness around normality ("One-Way ANOVA," 2015, p. 10). In case of unequal variances in the response data, Welch's ANOVA is used. After the Welch's ANOVA is conducted, the normal probability plot of the residuals is inspected with a fat pencil test. The elementary units, their groups, and the number of samples in each group (n) are outlined in Table 49; the associated Welch's ANOVA results are presented in Figure 89.

Elementary units	Pre-observation (Before) [Chapter 6]	Post-observation (After)
TT	30(n=20), 31(n=16), 33(n=28), 36(n=28), 41(n=28), 42(n=56), 66(n=20)	28(n=20), 32(n=19), 34(n=23), 49(n=23), 52(n=18), 69(n=22)
AT, PT	10(n=16), 11(n=76), 12(n=56), 16(n=48)	9(n=20), 11(n=19), 13(n=23), 14(n=41), 21(n=22)
Assembly code	3(n=16), 4(n=28), 6(n=28), 7(n=20), 8(n=20), 9(n=56), 10(n=28)	11(n=20), 12(n=18), 14(n=19), 15(n=23), 16(n=22), 17(n=23)
Pallet count	12(n=180), 20(n=20), 25(n=26)	12(n=83), 20(n=39), 25(n=23)
Production phase	end(n=160), full(n=40), start(n=26)	full(n=46), start(n=99)
Product family	a(n=20), b(n=84), c(n=96), d(n=26)	a(n=39), b(n=23), c(n=34), d(n=23), e(n=26)
DT	3(n=76), 5(n=36), 6(n=28), 7(n=20), 9(n=56)	5(n=68), 6(n=30), 7(n=28), 9(n=19)

Table 49: Elementary unit groups and sample size (n)

Elementary Unit	Before or After	ANOVA (Welch's)		
		F-value	P-value	R-Sq (%) 5, 10, 15, 20, 25, 30, 35, 40, 45, 50, 55, 60, …, 100
TT	Before	12.41	0.00	30.49%
	After	30.32	0.00	50.99%
AT, PT	Before	14.41	0.00	18.58%
	After	25.97	0.00	46.24%
Assembly code	Before	12.41	0.00	30.49%
	After	30.32	0.00	50.99%
Pallet count	Before	20.55	0.00	19.51%
	After	2.16	0.13*	4.15% *Note: P-value is > α
Production phase	Before	25.29	0.00	19.19%
	After	103.91•	0.00	41.75% •Note: 2 groups
Product family	Before	14.46	0.00	20.33%
	After	34.7	0.00	32.70%
DT	Before	13.56	0.00	23.34%
	After	17.34	0.00	28.00%

Figure 89: Welch's ANOVA results, testing correlation between elementary units and cycle time

For all but one test in Figure 89, the p-value is 0.00 and Ho is rejected ($p<0.05$); the mean cycle times between groups in the elementary unit are not the same. Thus, the variation in elementary unit grouping is significant in terms of explaining the variation in cycle time. The degree to which the elementary unit groups account for cycle time variation is expressed by R-sq; the R-sq values generally increase from before to after

(Figure 89). The next step is to further characterize these relevant elementary units into complexity variables in a model that further explains cycle time variation relative to the working designs in §9.2.2. Another explanation for the increase in R-sq is that additional elementary units, affecting the before design in particular, exist; though this paper focuses on the elementary units stated, the proposed approach can be used to test for additional elementary units. Additionally, there is likely to be system noise that is difficult to make explicit into an elementary unit. This interpretation may be supported by the F-values, which express a signal-to-noise ratio; the general trend in Figure 89 is that the F-values increase from before to after, with more system noise before versus after. It's important to note that the high F-value for production phase (after) is likely due to only two groups being compared (full and start). Production phase (after) is included in the Welch's ANOVA in Figure 89 for comparison, but it can more aptly be analyzed in a two sample t-test wherein a T-value versus F-value is calculated (T-value=10.19, p-value=0.00).

The one exception in the results (*), where the p-value is > 0.05, is for the pallet count (after). For the pallet count elementary unit, the p-value=0.00 before but the p-value=0.13 after; the before result rejects the null hypothesis while the after result accepts it. In other words, the pallet count contributes to variation in the cycle time population before but not after the design intervention; this means that pallet count may or may not be significant to understanding variation in cycle time. To compare before and after states of the assembly system in the subsequent investigative steps, it is important to include pallet count in this case because it is significant in the before cycle time population.

For count data where the range is > 10, a linear regression analysis is also conducted. This condition only applies for TT (before), TT (after), and AT (after). The linear regression analysis is conducted with a 95% degree of confidence, and the normal probability plots and residuals are checked for normality with a fat pencil test. For TT (before), the count range is 66-30=36; the regression result is p-value=0.54, R-Sq=0.2%. For TT (after), the count range is 69-28=41; the regression result is p-value=0.00, R-sq=20.4%. For AT (after), the count range is 21-9=12; the regression result is p-value=0.00, R-sq=33.0%. These results show that in the observation data, there is not a linear correlation present for TT before (0.54 > 0.05) but there is a linear correlation present for TT after (0.00 < 0.05) and AT after (0.00 < 0.05). The next steps in the investigative process inquire into reasons for this – to relate the working designs to complexity and cycle time.

9.2.2 Complexity variables from elementary units

This section begins by defining a complexity variable for each elementary unit: production phase (V), pallet count (PC), number of components (TT), number of different components (DT), number of picking tasks (PT), and number of assembling tasks (AT). These variables are grouped into a complexity ratio (r) for each assembly code (final product type) with a corresponding mean cycle time (X-bar$_{CT}$). These data points (r, X-bar$_{CT}$) are then plotted and analyzed with linear regression for comparative analysis. In total, 18 different production runs of unique assembly codes (i) are observed.

The observations relate to a production phase (V) in terms of the number of observations taken in the production run (n_i) and the position of the observations relative to the beginning (Equation 18) or end (Equation 19) of a production run. A full production run corresponds to Equation 19, versus Equation 18, based on the ANOVA analysis in Figure 89 (before), where the mean cycle time difference between end and full (0.23min/assembly) is less than the difference between beginning and full (0.61min/assembly). This suggests that the typical curve between production phase beginning and end may have a longer end tail, which is also why 0.5 is not a suitable V value for a full observation position (because 0.5 would assume a linear relationship). The exact curve cannot be drawn from the ANOVA, since this involves categorical data, but what is known is that the poles (beginning and end) are critical; accordingly, the beginning and end of the production run spectrum are emphasized as datum references in Equation 18 and Equation 19 respectively, which correspond to complexity values of 1 and 0. Equation 18 and Equation 19 were previously shown in §6.2.2.2.

$$V_i = 1 - \frac{n_i}{2Vol_{max}} \qquad \text{Equation 18}$$

$$V_i = \frac{n_i}{2Vol_{max}} \qquad \text{Equation 19}$$

In Equation 18 and Equation 19, i represents a given production run, where in this case i=1, 2, …, 10 before the design intervention and i=11, 12, …, 18 after; n_i represents the number of observation samples in i (i.e. number of assembly cycles, or number of final assemblies built, observed in the production run), where $n_i/2$ represents the midpoint of the observations; and Vol_{max} represents the maximum total number of final assemblies required to complete the order (i.e. production run volume) across all i (i.e. a theoretical observation maximum, or datum), which is 200 in this case.

The pallet count variable, PC, is calculated based on the ANOVA analysis (Figure 89) for the pallet count elementary unit. A relative ratio is based on mean cycle time ($Xbar_{j,k}$), where j is the pallet count (or number of finished assemblies that will fit on one pallet, j=12, 20, 25) and k=before or after the design intervention. This is outlined in Equation 20 with results in Table 50.

$$PC_{j,k} = \frac{Xbar_{j,k}}{\sum_{j=12,20,25} Xbar_{j,k}} \qquad \text{Equation 20}$$

Before or after (k)	Pallet count (j)	$Xbar_{j,k}$	$\Sigma_{j=12,20,25}Xbar_{j,k}$	$PC_{j,k}$
Before	12	3.67	10.77	0.34
	20	2.76	10.77	0.26
	25	4.34	10.77	0.40
After	12	2.16	6.31	0.34
	20	1.87	6.31	0.30
	25	2.28	6.31	0.36

Table 50: Calculating the values for the pallet count, PC, variable

The remaining elementary units from Figure 89 are correlated more specifically with the working design strategy (before and after) as follows. Each production run (i) relates to a particular assembly (or final product) code, which corresponds to a product family and dictates TT, DT, PT, and AT. How these factors (F) are divided between the two assembly builders, builder A and builder B, is determined by the process and layout design (working design strategy). TA and TB refer to the number of total components that builders A and B handle. DA and DB refer to the number of different components that builders A and B handle. PA and PB refer to the number of picking tasks that builders A and B perform. AA and AB refer to the number of assembly tasks that builders A and B perform. The degree of balance of the factors (F) between builders A and B can be explained by the ratio of the distribution (A-B) over the total (T), Equation 21.

$$FR_i = \frac{FA_i - FB_i}{FT_i} \qquad \text{Equation 21}$$

Equation 21 is used to calculate TR, DR, PR, and AR, where F=T,D,P, and A. The variables are then combined into a complexity ratio (r), Equation 22, with corresponding observed mean cycle times for the assembly code (X-bar$_{CT}$, in minutes/assembly) summarized in Table 51. [The grouping of the variables in Equation 22 is tested in Figure 90].

$$r_i = V_i + PC_i + |DR_i| + |TR_i| + |PR_i + AR_i| \qquad \text{Equation 22}$$

Before/ After	Assembly Code (i)	n_i	V_i	PC_i	TR_i	DR_i	PR_i	AR_i	r_i	X-bar$_{CTi}$
Before	1	10	0.03	0.34	0.28	0.20	0.13	0.13	1.10	2.40
	2	10	0.03	0.40	0.26	-0.20	-0.09	-0.09	1.07	2.90
	3	16	0.96	0.40	-0.35	-0.20	-0.40	-0.40	2.71	4.61
	4	28	0.07	0.34	0.46	-0.33	-0.38	-0.38	1.96	3.50
	5	10	0.98	0.34	-0.23	0.20	-0.33	-0.33	2.41	3.65
	6	28	0.07	0.34	-0.03	0.00	-0.64	0.45	0.63	2.62
	7	20	0.05	0.34	-0.83	0.00	-0.25	-0.25	1.72	2.79
	8	20	0.05	0.26	0.27	0.14	-0.09	-0.09	0.90	1.64
	9	56	0.14	0.34	-0.10	-0.11	-0.33	-0.33	1.35	2.64
	10	28	0.07	0.34	0.33	0.00	0.27	0.27	1.28	2.98
After	11	20	0.05	0.30	-0.11	-0.29	0.22	-0.89	1.42	1.49
	12	18	0.05	0.34	-0.10	-0.33	0.29	-1.00	1.53	1.63
	13	8	0.02	0.34	-0.13	-0.29	0.17	-1.00	1.61	1.76
	14	19	0.95	0.30	-0.16	-0.44	0.09	-1.00	2.76	2.89
	15	23	0.94	0.34	-0.06	-0.40	0.71	-1.00	2.03	2.06
	16	22	0.95	0.34	-0.12	-0.20	0.24	-0.62	1.98	2.65
	17	23	0.94	0.36	-0.06	-0.20	0.46	-1.00	2.10	2.39
	18	12	0.97	0.34	-0.23	-0.33	-0.23	-1.00	3.10	4.38

Table 51: Observation complexity variable values and corresponding mean cycle time

9.2.3 *Comparing before vs. after designs: Testing correlation between cycle time and the complexity ratio*

From Table 51, the points (r, X-bar$_{CT}$) are plotted as two series - before and after (the design intervention) in Figure 90. The correlation between mean cycle time and the complexity ratio is tested with linear regression, which is performed with a 95% degree of confidence. The normality of the mean cycle times is confirmed with a probability plot and fat pencil test.

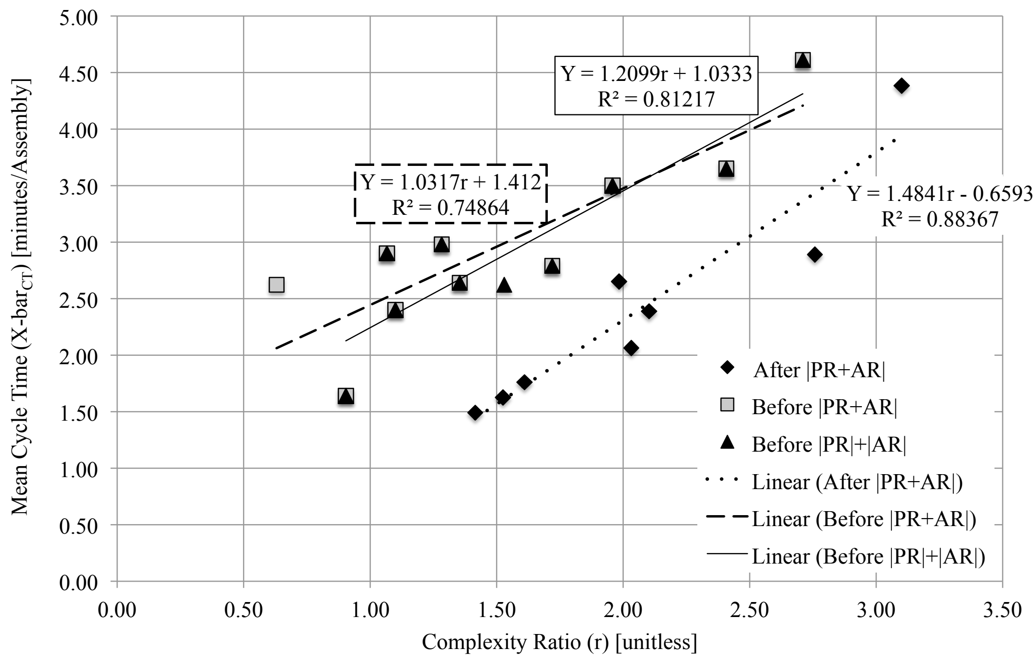


Figure 90: Mean cycle time vs. complexity ratio (before and after)

As shown in Figure 90, it is possible to consider the picking and assembling ratios, PR and AR, separately or together in terms of the complexity ratio. In the prior design, considering them separately yielded a higher R-sq value (0.81) than together (0.75). In the post-design, there is only a significant correlation when PR and AR are considered together. This aligns with the design strategies in place. In the prior design, the picking and assembling tasks are shared between the builders, so the aim is for the tasks to be equal between individuals. In the new design, the tasks are divided between the builders (picking or assembling), so the aim is for the tasks to be offset between individuals.

From Figure 90, it is clear that the new design (after) is organizing complexity with greater efficiency than the prior design (before) – for any given value of complexity, the mean cycle time is lower with respect to the new design (after) versus the prior design (before). The following question, however, arises: does the new system design yield a higher complexity value for a given assembly (final product) compared to the prior system design? With an assemble-to-order system with high final product variety, it is extremely challenging to create a direct observation comparison of this kind.

While a direct observation comparison is not viable, it is possible to use the models generated from the observation data to predict a mean cycle time using the plotted lines in Figure 90 with a complexity ratio. It's possible to determine the complexity ratio theoretically by analyzing the raw data (e.g. product information) with the alternative (before or after) working design strategy. In doing so, a direct pairwise comparison can be made between the same final product in the same observation conditions relative to the before and after design theories. From this direct comparison, it's possible to determine if the new design improves cycle time concurrently with complexity organization.

9.2.4 Comparing before vs. after designs: Testing pairwise comparison

To calculate a theoretical complexity ratio (r_T) of the assembly system before and after a design intervention, the investigative process outlined in §9.1 is applied, specifically step 10 in Table 48. This approach is further detailed in a matrix, Figure 91 (with the same shading as Figure 88), outlining the complexity variables with system conditions for observation and theoretical calculations.

	Before Product Structure, Pallet Count, & Production Phase (DT, TT, PT, AT, PC, & V)	**After** Product Structure, Pallet Count, & Production Phase (DT, TT, PT, AT, PC, & V)
Before Working Design Strategy (Y_B =)	**Observation Before** TA, TB, DA, DB, PA, PB, AA, AB → r → X-bar$_{CT}$ → (r_B, X-bar$_{CT,B}$)	Theoretical Before TA, TB, DA, DB, PA, PB, AA, AB → r → X-bar$_{CT}$ → (r_{TB}, X-bar$_{CT, TB}$)
After Working Design Strategy (Y_A =)	**Theoretical After** TA, TB, DA, DB, PA, PB, AA, AB → r → X-bar$_{CT}$→ (r_{TA}, X-bar$_{CT, TA}$)	**Observation After** TA, TB, DA, DB, PA, PB, AA, AB → r → X-bar$_{CT}$→ (r_A, x-bar$_{CT, A}$)
	10 pairs	8 pairs

Figure 91: Complexity variables for theoretical and observation calculations, before and after

As shown in Figure 91, the values of the complexity variables related to the product structure totals (DT, TT, PT, AT), pallet count (PC), and production phase (V) are held constant with the observation alternative. With this data, the distribution of work between builder A and B (TA, TB, DA, DB, PA, PB, AA, AB) is calculated using the contrasting working design strategy, which consequently creates new corresponding ratios (TR, DR, PR, AR). With these complexity variables, the theoretical complexity ratio (r_T) is calculated. Using r_T and Y= (the correlation between mean cycle time and the complexity ratio for the given working design strategy, Figure 90), the theoretical mean cycle time ($x\text{-bar}_{CT,\,T}$) is calculated. These results for each assembly code (i) are shown in Table 52.

Before/ After	Assembly Code (i)	V_i	PC_i	TR_i	DR_i	PR_i	AR_i	r_{iT}	$X\text{-bar}_{CTi,\,T}$
After	1	0.03	0.34	-0.07	-0.20	0.50	-1.00	1.13	1.02
	2	0.03	0.40	-0.09	-0.40	0.27	-1.00	1.65	1.78
	3	0.96	0.40	-0.13	-0.40	0.20	-1.00	2.69	3.33
	4	0.07	0.34	-0.27	-0.67	-0.38	-1.00	2.72	3.38
	5	0.98	0.34	-0.08	-0.40	0.33	-1.00	2.46	2.99
	6	0.07	0.34	-0.17	-0.67	-0.09	-1.00	2.33	2.80
	7	0.05	0.34	-0.09	-0.67	0.25	-1.00	1.90	2.16
	8	0.05	0.26	-0.20	-0.43	-0.09	-1.00	2.03	2.35
	9	0.14	0.34	-0.12	-0.33	0.08	-0.08	0.93	0.72
	10	0.07	0.34	-0.15	-0.50	0.00	-0.91	1.97	2.27
Before	11	0.05	0.30	0.71	0.14	0.11	0.11	1.42	2.76
	12	0.05	0.34	-0.12	0.00	-0.29	-0.29	1.07	2.33
	13	0.02	0.34	0.00	-0.14	-0.33	-0.33	1.17	2.45
	14	0.95	0.30	0.13	-0.33	-0.27	-0.27	2.25	3.76
	15	0.94	0.34	0.00	0.20	0.00	0.00	1.48	2.83
	16	0.95	0.34	-0.01	0.20	0.33	0.33	2.17	3.65
	17	0.94	0.36	0.22	-0.20	-0.08	-0.08	1.88	3.31
	18	0.97	0.34	-0.20	0.00	-0.54	-0.54	2.59	4.16

Table 52: Theoretical complexity variable values and associated mean cycle time

From Table 52 and Table 51, mean cycle time pairs (before, after) are created for direct comparison: ($X\text{-bar}_{CTi,B}$, $X\text{-bar}_{CTi,TA}$), n=10 and ($X\text{-bar}_{CTi,TB}$, $X\text{-bar}_{CTi,A}$), n=8. With a paired t-test (95% degree of confidence), the effect of the design intervention on mean cycle time is tested. Ho states that the difference between the after mean cycle time and the before mean cycle time is 0. The alternative is that the difference does not equal 0. The after-before difference is plotted on a probability plot and checked with a fat pencil test to confirm normality; results are shared in Table 53 and Figure 92.

	n	Mean	Standard deviation	Mean standard error
After Mean Cycle Time	18	2.34	0.90	0.21
Before Mean Cycle Time	18	3.05	0.73	0.17
Difference	18	-0.72	0.64	0.15

Table 53: Paired t-test results, 95% confidence, after – before mean cycle time

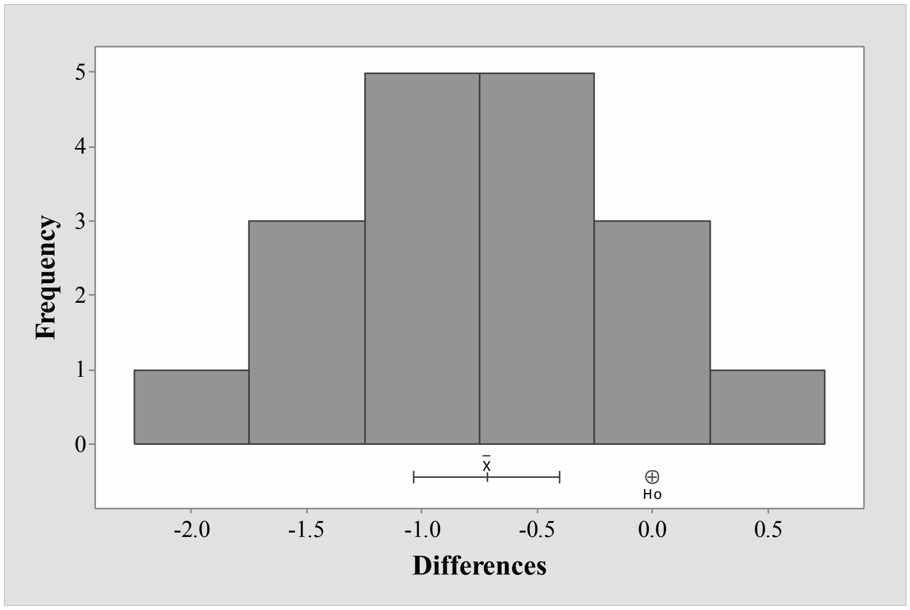


Figure 92: Paired t-test histogram of differences, after - before mean cycle time

From the paired t-test analysis, the T-value is -4.78 with a corresponding p-value of 0.00. Since p<α (where α=0.05 for a 95% degree of confidence), the null hypothesis is rejected and it can be concluded that there is a statistically significant mean difference in mean cycle time before and after the design intervention. The mean cycle time is lower after the design intervention (2.34 ± 0.90 minutes/assembly) than before the design intervention (3.05 ± 0.73 minutes/assembly), with a statistically significant mean difference of -0.72 (95% confidence interval, -1.04 to -0.40) minutes/assembly. In other words, the mean cycle time was reduced by 0.72 minutes/assembly by the participatory design intervention, specifically by the after working design strategy outcome of the participatory design events when compared to the before working design strategy.

9.3 Conclusion

How can the differentiated designs be evaluated in a before versus after socio-technical system model comparison? This question is important to understanding the impact of the differentiated designs. This chapter answers this question with an investigative approach for an observation operational model that analyzes both pre- and post-observation. The post-observation data reflects the working design strategy after the differentiated designs (§8.1-8.3) have been implemented; the pre-observation data reflects the working design strategy prior to the differentiated designs (the initial observation operational model in Chapter 6). They represent the before and after conditions in the re-design project at hand – the re-design of an assembly production system and socio-technical system archetype.

The investigative approach and its results are as follows. From observation data (n=226 before, n=145 after), the relationships between elementary units and the cycle time population are tested with Welch's ANOVA and regression analysis. The elementary units are then translated into a complexity ratio via complexity variables to relate the working design strategy to the mean cycle times. The correlation between the complexity ratio and mean cycle time is tested with regression analysis (95% degree of confidence); R-sq=0.75 and 0.81 (before working design) and R-sq=0.88 (after working design). The regression plot illustrates that the after working design strategy (differentiated designs §8.1-8.3) organizes the complexity ratio (r) more efficiently compared to the after working design strategy by virtue of its lower line placement on the mean cycle time versus complexity ratio plot (Figure 90). These correlations also serve as a model to predict theoretical values for mean cycle time direct comparison. The before and after mean cycle times for theoretical and observation values are compared with a paired t-test; the mean cycle time is found to be lower after the design intervention versus before with a statistically significant mean difference (after – before) of -0.72 minutes/assembly (95% degree of confidence).

The developed investigative approach proves successful in analyzing and comparing two working designs in an assemble-to-order production system (a STS archetype) in an observation operational model. In doing so, the approach evaluates the design intervention and here finds that the differentiated designs have impacted the system behaviour (complexity ratio, r) and improved its function (cycle time reduction). The trustworthiness and validation of this chapter research are evaluated in Chapter 11. The limitations of this chapter research are examined in Chapter 12.

Based on these conclusions, "Emic system evaluation" is a critical step after "Differentiated designs" (Figure 86, Chapter 8) in this dissertation's model for re-designing a socio-technical system, summarized systematically with an IDEF0 model in Figure 93. Figure 93 is related to the research questions in the dissertation study as follows. The inputs, mechanisms, and reference models relate to research question 2 (shown in Figure 93 in `Courier font`). The questions, outputs, and constraints relate to research question 3 (shown in Figure 93 in Calibri font).

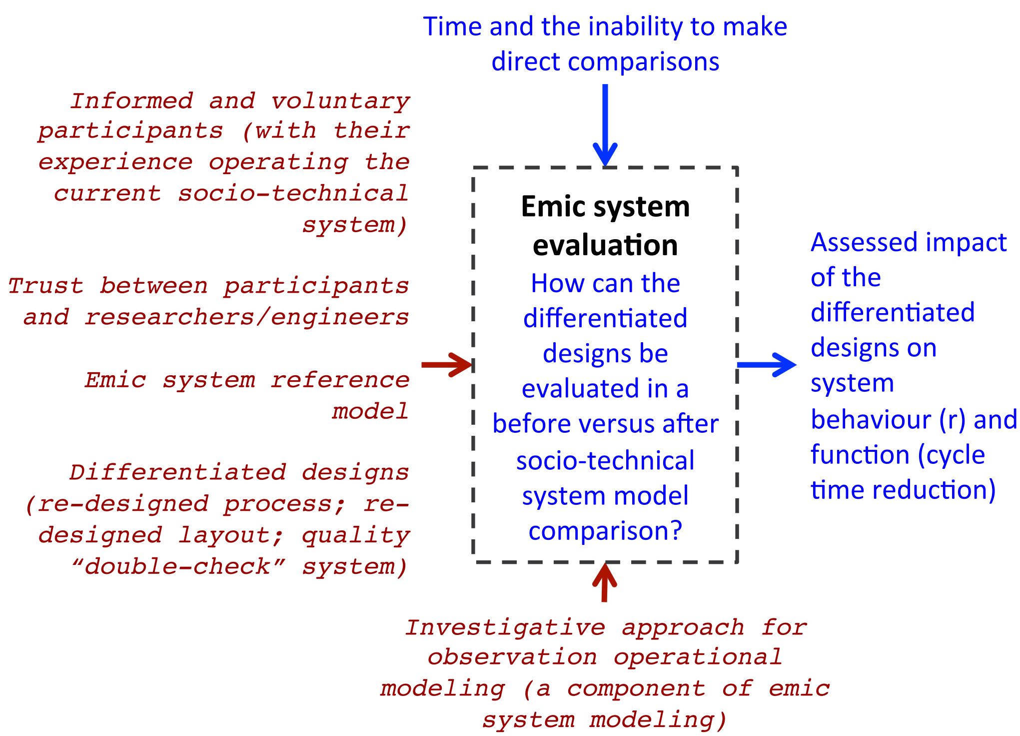


Figure 93: Emic system evaluation IDEF0

The position of "Emic system evaluation" (Figure 93) in this dissertation's model for re-designing a socio-technical system is shown in Figure 94.

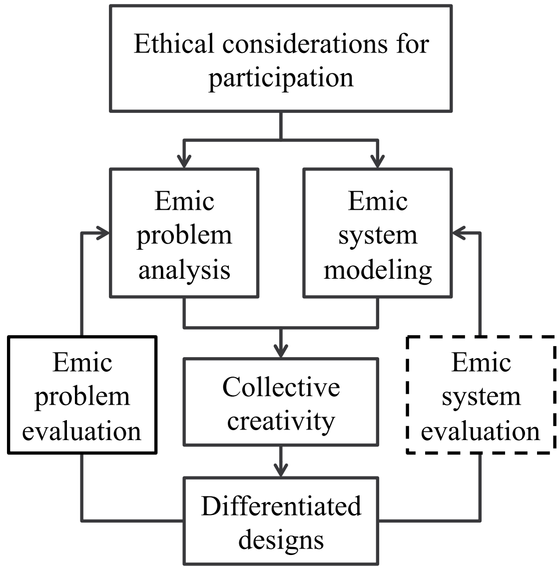


Figure 94: Emic system evaluation in the developed model for re-designing a socio-technical system

10 Emic problem and re-design experience evaluation in socio-technical system re-design

After establishing differentiated designs (Chapter 8), another next step in developing a participatory approach for re-designing a socio-technical system is to evaluate the re-designs in terms of the emic problem (defined in Chapter 5). Evaluation is positioned late in engineering design methodology (Pahl et al., 2007, p. 16) and systems design methodology (Whitten and Bentley, 2007, p. 30). System evaluation has not been explicitly related to STS theory in re-design (Table 5).

In turn, the research in this chapter asks: How do the participants evaluate their differentiated designs and ideas (Chapter 7 and 8) in terms of the emic problem (Chapter 5)? Also, how do they evaluate their participatory re-design experience? This chapter investigates these questions with an emic (insider/participant) approach, grounding the research in qualitative methodology (§3.2) and further developing the descriptive study II of design research methodology (§3.1, Figure 6). The chapter's research questions are explored *in situ* in the re-design of an assembly production system and socio-technical system archetype. The industrial context and participants are described in §3.4.

Consequently, this chapter is organized into two primary sections. The first section (§10.1) analyzes participant evaluations of the re-designs, their importance and their impact in relation to the success criteria (critical issues) defined in the emic problem analysis (from Chapter 5). In effect, the emic problem analysis from Chapter 5 serves as a reference model to compare with the post-survey results. The second section (§10.2) analyzes participant evaluations of the re-design experience, including the co-design experience and the re-design experience as a whole. The post-survey is based on the participants' experience within the study and in relation to the re-designs in the co-design events, post-observation, and their work practice. The re-designs were not fully implemented across the industrial context at the time of the post-survey; this was dependent on implementation of the new training program, which is beyond the scope of this research. The post-survey was completed anonymously by seven participants. **Any identifying or confidential information was removed from the participant responses and post-survey questions.**

10.1 Participant evaluations of the re-designs

10.1.1 Participant evaluations of the importance of the re-design ideas

Participants were asked to evaluate 15 of the re-design ideas. These were the re-designs that the participants worked with the most in the co-design events, post-observation, and their work practice. The post-survey results for the following question are presented in Table 54. *The following design ideas for the [assembly] process, layout, and training arose out of the design events: Please place a "1" and "2" beside the two design ideas that you think are the* ****most**** *important. Please place an "X" beside the two design ideas that you think are the* ****least**** *important.*

Participant responses, n=7							Re-design description
				X			Changing the location of the build table (rotating it 90 degrees)
				X		X	New layout diagram (designating locations for pallets, etc.)
			X				Moving the [x] machine and learning how to use it to its full potential
2	X				1		Grid on the table with locations for the different [assembly] materials
1		X				X	Labeling system for the grid on the table and pallets (colour-coded, laminated tags with Velcro)
		2	1		2		Two roles for the builders – one picker, one assembler
		X			X		Checklist for the different builder tasks (for the picker, assembler, and some shared)
	2			1		1	Demonstration of the [assembly] process with the new builders (setting up the example with them)
						2	Specific people designated as a "[assembly] trainer"
							Sample of the paperwork with different areas highlighted to explain it
	X		X				Making [assemblies] a priority for the lead hand, secondary to receiving
							Communication board (including average times, language (e.g. UPC, shippers, CHEP), etc.)
		1		2			Walkie-talkies for the builders to communicate with others (e.g. lead hands, material handlers)
X	1	3			X		All [platforms] to come in a coffin-like shipper
			2				[Assembly] training checklist (including showing how to block and brace, shake test, etc.)

Table 54: Participant evaluations of the most and least important re-designs

The responses in Table 54 show a range in prioritization of the different re-design ideas. This variation could be related to personal interpretations, but it is also very likely related to the participant's work role. The impact that the different re-designs have on different aspects of the assembly production system relates differently to the different work roles. In other words, what is important to one person may be different to another person depending on their work role, which is related to how they experience their assembly production system.

In addition to the evaluation of re-designs in Table 54, the participants were also asked to identify any other re-design ideas not included in the brief summary in Table 54. The post-survey results for the following question are provided in bullet points. *Are there any other design ideas that you think are important?*

- Enforcing and clarifying the new design, sometimes [assemblies] are not being set up properly as per the new design (e.g. set up the old way, and set up backwards so the flow is disrupted)
- Space – flow is disrupted by entrances and exits from [assembly] area being blocked by pallets – nowhere to put completed products
- I think you covered all aspects

These re-design ideas help to critique the implementation of the current re-design and position subsequent re-designs in the industrial context. They also reinforce the importance of a full implementation of the re-designs across the industrial context in order to have consistent work practice with the re-designs.

10.1.2 Participant evaluations of re-design impact with success criteria

Participants were asked to evaluate the impact of the re-designs. Each question was aligned with the emic codes from the pre-interview problem analysis (Chapter 5). The eight critical issues/codes from the emic problem analysis in Chapter 5 were included (14, 19, 11, 15, 12, 13, 9, and 10); a few additional codes that were thought to potentially relate to the re-designs were also included. Not all 26 codes were included because the survey would become considerably more burdensome for the participants (its current length, 5 pages, may be a potential reason why only 7 participants took part).

The post-survey results for the following question are presented in Table 55. *To what extent do you agree or disagree with each of the following statements when comparing the new [assembly] process design to the old design? Select *__one__* circle for each statement. The new design refers to the process, layout, and training designs that you participated in creating and working with.*

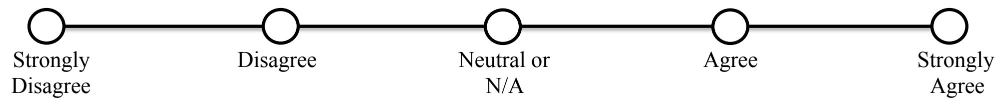


Figure 95: Agreement scale

a) The new design has improved builder responsibility and independence.

b) The new design has improved quality by better ensuring that the correct number of each material is used.

c) The new design has improved the utilization of limited room and space.

d) The new design has improved the organization of the [assembly] materials and components.

e) The new design has improved the order of tasks involved in [assembly] making.

f) The new design has improved the division of work between the builders (i.e. deciding who does what).

g) The new design has improved the ability for new builders to learn the [assembly] process and work.

h) The new design has improved the flow of [assembly] materials, components, and final [assemblies].

i) The new design has improved the flow of people involved in [assembly] work.

j) The new design has improved the ability for us to work smarter not harder when building [assemblies].

k) The new design has improved the communication between different people involved in building [assemblies].

l) The new design applies to us.

m) The new design is fair (or just).

To calculate the average agreement amongst the 7 participants with the statements (a) to (m), the scale is given the following values: strongly disagree (score=1); disagree (score=2); neutral or n/a (score=3); agree (score=4); and strongly agree (score=5). The results are shown in Table 55.

Statement	Impact average rating score (IA)
a *(n=6)*	3.8
b *(n=7)*	3.9
c *(n=7)*	3.0
d *(n=7)*	3.4
e *(n=7)*	4.0
f *(n=7)*	3.9
g *(n=7)*	3.3
h *(n=7)*	3.3
i *(n=7)*	3.4
j *(n=7)*	3.4
k *(n=7)*	2.9
l *(n=7)*	3.7
m *(n=7)*	4.0

Table 55: Average score with the improvement statements (1=strongly disagree; 5=strongly agree; n=sample size)

In order to assess the impact that the re-design has made in relation to the pre-interview problem analysis and post-survey evaluation, the pre-interview emic codes are aligned with the post-survey statements into success criteria (cf. Table 56).

Success criteria	Pre-interview emic code	Post-survey statement
14h	Improve flow (14)	The new design has improved the flow of [assembly] materials, components, and final [assemblies] (h).
14i	Improve flow (14)	The new design has improved the flow of people involved in [assembly] work (i).
19e	Improve build sequence, division of work (19)	The new design has improved the order of tasks involved in [assembly] making (e).
19f	Improve build sequence, division of work (19)	The new design has improved the division of work between the builders (i.e. deciding who does what) (f).
13d	Organize, designate position for materials (13)	The new design has improved the organization of the [assembly] materials and components (d)
9g	Training builders (9)	The new design has improved the ability for new builders to learn the [assembly] process and work (g)
11b	Ensure quality (11)	The new design has improved quality by better ensuring that the correct number of each material is used (b).
23j	Working smarter not harder (23)	The new design has improved the ability for us to work smarter not harder when building [assemblies] (j)
10a	Establish builder responsibility, autonomy (10)	The new design has improved builder responsibility and independence (a).
12c	Limited room and space (12)	The new design has improved the utilization of limited room and space (c).
17l	Assembly line differentiation (17)	The new design applies to us (l)
0m	Fairness arose in the participatory design event	The new design is fair (or just) (m)
7k	Ease of lead hand and builder communication (7)	The new design has improved the communication between different people involved in building [assemblies] (k)

Table 56: Success criteria: Alignment between pre-interview emic code and post-survey statements

To understand the change that the re-design has had on the initial pre-interview problem analysis, the following variables and equations are utilized. For the pre-problem analysis condition (before re-design), the following variables are utilized in relation to the pre-interview emic codes that correspond to the success criteria (per Table 56):

- M_{ij} = magnitude of occurrence value
- W_{ij} = weighted adjacency value
- SC_b = value of the success criteria before the re-design (see Equation 23)

For the post-problem analysis condition (after re-design), the following variables are utilized in relation to the post-survey statements that correspond to the success criteria (per Table 56):

- IA = impact average agreement
- SC_{impact} = value of the success criteria impact (see Equation 24)
- $IA_{neutral}$ = 3
- IA_{max} = 5
- SC_a = value of the success criteria after the re-design in relation to the before success criteria (see Equation 25)

$$SC_b = M_{ij} + W_{ij} \qquad \text{Equation 23}$$

$$SC_{impact} = \left(\frac{IA - IA_{neutral}}{IA_{max} - IA_{neutral}}\right) SC_b \qquad \text{Equation 24}$$

$$SC_a = SC_b - SC_{impact} \qquad \text{Equation 25}$$

Success criteria	Before re-design			After re-design		
	M_{ij}	W_{ij}	SC_b	IA	SC_{impact}	SC_a
14h	3	17	20	3.3	3.0	17.0
14i	3	17	20	3.4	4	16.0
19e	3	14	17	4.0	8.5	8.5
19f	3	14	17	3.9	7.7	9.4
13d	3	13	16	3.4	3.2	12.0
9g	3	10	13	3.3	2.0	11.1
11b	2	9	11	3.9	5.0	6.1
23j	2	5	7	3.4	1.4	5.6
10a	3	8	11	3.8	4.4	6.6
12c	9	6	15	3.0	0.0	15
17l	1	3	4	3.7	1.4	2.6
0m	1	3	4	4.0	2.0	2
7k	1	2	3	2.9	-0.2	3.2

Table 57: Success criteria values before and after re-design

The values in Table 57 are further interpreted as follows. The relative impact (post-re-design state) that the re-design has had in relation to the initial emic problem analysis (pre-re-design state) can be evaluated as lines on a radar chart, with the success criteria scales positioned as axes. This type of evaluation compares the success criteria value before the re-design (SC_b) to the success criteria value remaining after the re-design (SC_a), as pictured in Figure 96. In this situation, ideally the SC_a values would all be 0 to completely improve all of the success criteria in their entirety. This illustrates the relative improvement in the success criteria that the re-design has had in relation to the initial problem analysis, and the remaining problem analysis in relation to the success criteria, as evaluated by the participants. In this illustration, the area between the SC_b and SC_a lines is the relative amount of improvement. The area between the SC_a and the center of the radar diagram is the remaining problem analysis.

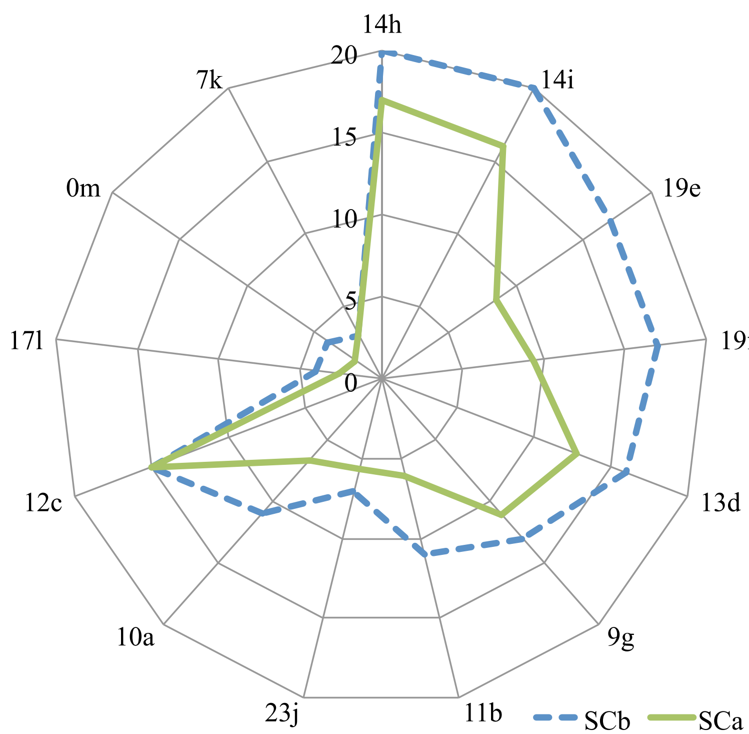


Figure 96: Before (SC_b) versus after (SC_a) problem space in relation to the success criteria (SC)

Figure 96 illustrates that the overall problem has not been completely solved in relation to achieving the participants' success criteria (if so, the green line would be at the center of the radar chart). The overall size of the problem has shrunk in relation to achieving the success criteria. The SC_b area in Figure 96 (from the SC_b line to the center of the radar chart) is 492.37 success criteria units^2. The SC_a area in Figure 94 (from the SC_a line to the center of the radar chart) is 250.19 success criteria units^2. The % change in problem area, between the SC_barea and the SC_aarea, is defined in Equation 26 and calculated as -49.19% (decrease after re-design).

$$\% \, change \, in \, problem \, area = \frac{SC_a area - SC_b area}{SC_b area} x100 \qquad \text{Equation 26}$$

This visualization in Figure 96 and its analysis highlights the improvement that has been made while also providing a new datum to align further re-design efforts with. This supports continuous learning in re-design, drawing from participant reflection. The visualization and analysis in Figure 96 also shows consistency in the participant responses; point 12c did not change before versus after the re-design intervention and this was a constraint, so this is an example of a trustworthiness and validation check.

10.1.3 Participant evaluations of future improvements to the re-designs

In the post-survey, participants were asked to evaluate the re-designs for future improvements. The post-survey responses were given for the question: *Are there any other improvements with new design(s) that you can think of? Please explain.*

- "With much larger [assemblies] (more than 5 items), I think a new design needs to applied to those ones. X assemblies have up to 12 products."
- "Improved communication (strongly disagree): there still needs to be a more reliable form of communication between X builders and material handlers. X has no dispatch station and builder are not told at the beginning of shift which material handlers is on [assemblies], so it is often unknown who builders should go to and we are often re-directed 2-3 times."
- "Maybe a self-count every hour. Mistakes are still happening."

These participant responses highlight opportunities to question the re-design further and in turn motivate further re-design in the industrial context.

10.1.4 Participant evaluations of a good design

Participants were asked to evaluate what makes a good design. Participants could reflect in terms of their specific experience in this re-design project or generalize from it to evaluate a design more broadly. The post-survey results for the following question are organized into themes by the researcher and presented in Table 58. *Based on your experience with the new and old X assembly designs (process, layout, and training), what* *do you think makes a good design? You can answer this specifically (for process, layout, and/or training) or in general (considering all of them together) or both.*

Participant responses	General considerations of a good design														
	Shared understanding	Information	Process	Simplicity	Communication	Accessibility	Clarity	Consistency	Flow of materials	Layout	Roles & Responsibilities	Quality	From the beginning	Organization	Training
"Communication is ideal"					x										
"Having the same layout for all helps keep people doing the same thing, all on the same page"							x	x		x					
"Good flow of components and finished products"									x						
"The double-check element of the new design ensures quality control and accountability for mistakes"											x	x			
"Simplified process with clear and distinct positions (ex. picker and assembler)"			x	x			x				x				
"Solid line of communication with all employees involved in the process (builders and material handlers)"					x										
"More info on specific duties for each builder"		x									x				
"A good design is best defined as all parties understanding the job at hand"	x														
"Diagrams that have explanations and a clear visual example are the best ways to understand"	x				x										
"A good design would start with the initial start up"													x		
"Organized [assembly] materials – no crowding"										x				x	
"Trained employees"															x
"Roles and responsibilities determined"											x				
"Proper documentation / counts recorded accurately"					x							x			
"Communication and accessibility to lead hand and material handler"					x	x									
"Limited work area is an issue. Sometimes not enough space to line up all products and [assembly components] on one side – it defeats the picker and assembler job division. Hard to move in/out empties and finished skids"										x	x				

Table 58: Participant evaluations of a good design

The general considerations of a good design in Table 58 are helpful takeaways that can be utilized to orient, measure, and compare subsequent re-designs within this industrial context. The general considerations can also be utilized to question re-designs in other industrial contexts.

10.2 Participant evaluations of the re-design experience

10.2.1 Participant reflections on the co-design events

In the second co-design event (PD3 in Chapter 7), the participants were asked to reflect on their co-design experience. The participants were asked: *How would you describe your experience with participatory design?* The individual responses to this question are included in Appendix P and are summarized into areas of strength and areas of improvement in Table 59 that were inquired into further in the study.

<table>
<tr><th colspan="2">Participant co-design reflections</th></tr>
<tr><th>Areas of strength</th><th>Areas for improvement</th></tr>
<tr><td>

Collaboration between different employee groups
Productive
Group involvement, brain storming, feeding off each other's ideas
Involving different aspects of thinking
Different settings
Group discussions
Mistake free process
Great – better and easier
Informative
A lot of ideas out on the table
Enjoyed experience, included, employee feedback is important
Great time

</td><td>

Smaller groups with more time, more often; making things more concrete; Progress has been made but we need to elaborate
A third co-design event was held to focus on these concerns - making some of the ideas from the PD3 event more concrete in small groups
More time with multiple products on the ground – big issues; research comparing build times using the old method to build times using the new method
The post-observation inquired into this
Not sure if full-timers will be ok with the new process
Full-timers are involved as participants in the study

</td></tr>
</table>

Table 59: Participant co-design reflections after the second co-design event (PD3)

As Table 59 shows, the subsequent phases of the study built on this participant feedback. This feedback can also be utilized within other re-design efforts within the industrial context that utilize co-design. This feedback can also be generalized to question if these factors may be important to participants in other co-design activities and accordingly aid in the design of other co-design events.

10.2.2 Participant evaluations on the re-design experience as a whole

In the post-survey, participants were asked to comment on their participation in the research study as a whole with the following questions: *Through your participation in this research study, is there anything that you especially liked participating in?* and *Through your participation in this research study, is there anything that you did ***not*** like experiencing or participating in?* The participant responses to these questions are summarized in Table 60, corresponding to the participants' likes and dislikes.

Participant reflections on their experience in the research study	
Likes	Dislikes
• "I liked hearing other people's ideas and thought process" • "The pizza lunch!" • "The development process. I enjoyed being heard and I enjoyed being part of creating a solution for improvement" • "All of it" • "Brainstorming" • "Creating and implementing the ideas and processes"	• "I would have liked to see the process being used" • "Logging the issue" • "No" • "No"

Table 60: Participant reflections on likes and dislikes in the research study

In the post-survey, participants were also asked to reflect on the design process more generally. Participant responses are shown in bullet points following the post-survey question. *Based on your experience with the design process in this study, what do you think makes a good design process?*

- "Working made easier (smarter)"
- "Communication, double check and accountability"
- "One that emphasizes efficiency and is communicated well"

In the post-survey, participants were also asked to evaluate their participation in relation to the attributes of participatory design that were part of the aims of this research (e.g. participant voice and say (influence, such as decision-making)). Accordingly, the following post-survey question was asked: *Through your participation in this research study, how would you rate the following?*

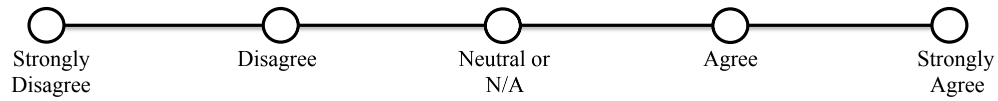


Figure 97: Agreement scale

a) I believe that my voice was heard in the design process.
b) I had a say (or influence) in the design process.
c) I participated in decision-making in the design process.
d) I participated in creating positive change in my work environment.
e) I learned new things from my participation in the design process.

To calculate the participant average agreement with each of the statements (a) to (e), the agreement scale is given the following values: strongly disagree (score=1), disagree (score=2), neutral or n/a (score=3), agree (score=4), and strongly agree (score=5). The results are shown in Table 61.

Statement	n for each score					Average response
	Strongly disagree (1)	Disagree (2)	Neutral or n/a (3)	Agree (4)	Strongly agree (5)	
9a *(n=7)*	0	1	0	3	3	4.1
9b *(n=7)*	0	1	1	4	1	3.7
9c *(n=7)*	0	2	0	4	1	3.6
9d *(n=7)*	0	2	0	5	0	3.4
9e *(n=7)*	0	1	1	3	2	3.9

Table 61: Average score with the participation statements (1=strongly disagree; 5=strongly agree)

The participant average responses in Table 61 are all above neutral (>3). The lowest average score (3.4 – neutral) relates to creating positive change. Since all of the re-designs have not been implemented across the industrial context this makes sense. The highest average score (4.1 – agree) relates to participants agreeing that their voice was heard in the design process. In total, there were 7 disagree scores (20%), 2 neutral scores (5.7%), 19 agree scores (54.3%), and 7 strongly agree scores (20%). In other words, 74.3% of the scores agreed or strongly agreed with statements (a) to (e).

Ideally, the values in Table 61 would all have been closer to 5. These values reflect an anonymous response, which hopefully supported honesty. The participant responses have been generally positive in the other post-survey questions (e.g. the participants did not cite any major improvements that could be made and no major dislikes). As a result, it is difficult to assess how these participatory aspects could have been improved. A question to inquire directly into how each of the statements (a) to (e) could be improved could be a useful question in other studies, or a statement to the effect of "If you disagree with any of these statements, please explain how this could be improved."

At the same time, it is important to note the range of participant responses that led to the average calculations in Table 61. The individual responses highlight a wide range of scores. The high scores indicate that there was an opportunity for participants to participate authentically in relation to these statements. This does raise the question that the fulfillment of the statements (a) to (e) are not only dependent on the research design and its facilitation but are also dependent upon a participant's choice to participate. The more a participant participates, which could include multiple phases of the study and/or the extent to which s/he participates (e.g. raises his/her voice, often, in meaningful ways to him/her, etc.), the more s/he is likely to reap the benefits of the opportunity for authentic participation. Future studies could state this directly at the beginning of the study, to be forthcoming with participants.

10.2.3 Participant evaluations on the extension of the re-design approach

In the post-survey, participants were also asked to evaluate the transferability of the re-design approach that they experienced to other manufacturing environments. The post-survey questions (italicized) are followed by the participant responses. *Are there other situations in manufacturing that you think a participatory design approach, like the one you experienced, could be used?*

- “Packaging operations… procedures can be tested to determine changes that can increase productivity”
- “Yes!! A lot of manufacturing employees stand around half the time they are at work. A design program should be used so workers have something to do”
- “Flow of work/organization and delegation of roles and responsibilities can be used in most manufacturing situations”

*Are there other situations in manufacturing that you think a participatory design approach, like the one you experienced, could *__not__* be used?*

- “Material handling responsibilities”
- “No”

These responses provide some insight into the transferability of the re-design approach taken in this study from the participants’ perspectives.

10.3 Conclusion

The participant evaluations of the re-design experience (§10.2) included highlighting 12 different areas of strength (Table 59) in reflections on their co-design experience in the second co-design event (Chapter 7). The three areas for improvement were further addressed in the third co-design event (Chapter 8). In general, participants highlighted both likes and dislikes in their re-design experience as a whole (Table 60), which highlighted being a part of idea generation as a common thread of enjoyment. Dislikes included “logging the issue” and wanting to “see the process being used.” Participants also emphasized communication, accountability, efficiency, and working smarter not harder as qualities of a good design process. Participants evaluated their participation in alignment with the qualities of authentic participation in the PD literature (e.g. participation with a heard voice and say). The participant responses spanned a range, with overall averages >3 (neutral) for each of the five criteria and 74.3% of the scores agreeing or strongly agreeing with the participation statements (Table 61). The participants suggested some examples of the broader transferability of the re-design approach that they experienced to other manufacturing contexts.

The participant evaluations of the re-designs (§10.1) included the following. Participants ranked fifteen of the re-design ideas in terms of their importance (Table 54). These were the re-designs that the participants worked with the most in the co-design events, post-observation, and their work practice. The highest ranked ideas overall included:

1. Demonstration of the assembly process with builders;
2. Two roles for the builders – one picker, one assembler;
3. Walkie-talkies for the builders to communicate;
4. Grid on the table for quality check;
5. Labeling system for the grid;
6. Platform shipper style changed;
7. Assembly training checklist; and
8. Specific "assembly trainer" position;

The impact of the re-design was assessed in relation to the pre-interview problem analysis – aligning critical issues/codes from the problem analysis (Chapter 5) with the post-survey statements into 13 success criteria (Table 56). The visual representation (Figure 96) of the analytical analysis (Table 57) showed that the overall size of the problem has shrunk from the before re-design condition (pre-interview problem analysis) to the post re-design condition (post-survey responses), in relation to success criteria improvements (an overall reduction of 49.19% from before to after). The participants highlighted further opportunities to question re-design in their industrial context as well as general reflections on a good design (16 considerations in Table 58). The trustworthiness and validation of this chapter research are evaluated in Chapter 11. The limitations of this chapter research are examined in Chapter 12.

Based on these conclusions, "Emic problem evaluation" is a critical step after "Differentiated designs" (Figure 86, Chapter 8) in this dissertation's model for re-designing a socio-technical system, summarized systematically with an IDEF0 model in Figure 98. Figure 98 is related to the research questions in the dissertation study as follows. The inputs, mechanisms, and reference models relate to research question 2 (shown in Figure 98 in `Courier font`). The questions, outputs, and constraints relate to research question 3 (shown in Figure 98 in Calibri font).

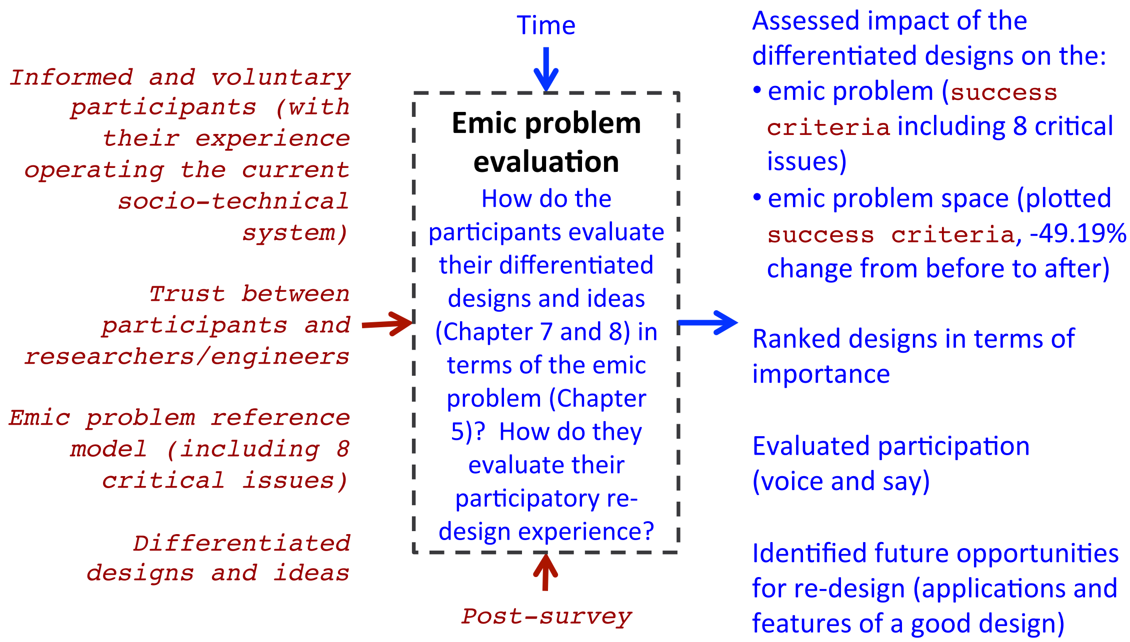


Figure 98: Emic problem evaluation IDEF0

The position of "Emic problem evaluation" (Figure 98) in this dissertation's model for re-designing a socio-technical system is shown in Figure 99.

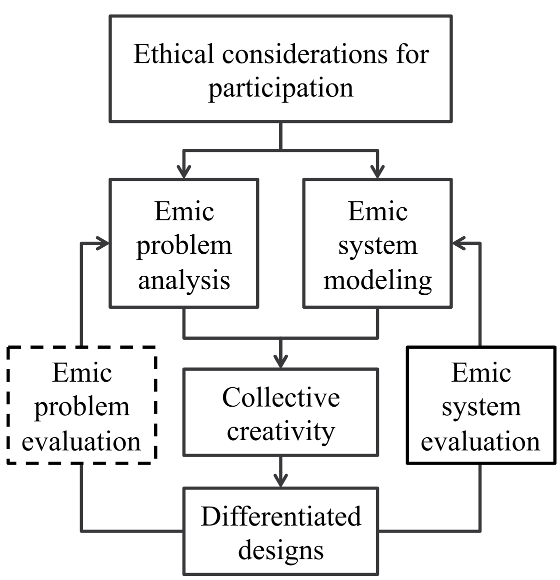


Figure 99: Emic problem evaluation in the developed model for re-designing a socio-technical system

11 Discussion aligning the research questions and findings

This discussion is structured in relation to the research questions (RQ), as stated in Table 62. The research questions are addressed in the discussion (per the border and shading in Table 62) in §11.1, §11.2, and §11.3. These results are then discussed in terms of the literature in §11.4.

Social science (Soc) phrasing (human participant research)	Engineering (Eng) phrasing	Design research methodology (DRM) phrasing
1. How can engaging socio-technical system operators as participants in re-designing an assembly production system develop an approach for re-designing socio-technical systems that operationalizes human value and potential?	1. What is the re-design model to re-design an assembly production (socio-technical) system with stakeholder participation, human value, and human potential?	1. How can the practice of re-designing a socio-technical system with operator participation be demonstrated and defined?
2. How do alternative (e.g. social science) and existing engineering design knowledge, practice, theory, methods, tools, techniques, etc. mis/align with this participatory re-design and why?	2. What are the inputs and mechanisms to re-design an assembly production (socio-technical) system with stakeholders? How do these compare to traditional engineering inputs and mechanisms?	2. What success criteria, reference models, and support are relevant to the practice of re-designing a socio-technical system with operator participation? How are the success criteria, reference models, and support developed?
3. What opportunities, problems, and questions arise (social and technical) in relation to the participatory re-design of the assembly production (socio-technical) system and why are they significant?	3. What are the constraints, outputs, and outcomes to re-design an assembly production (socio-technical) system with stakeholders?	3. How are the success criteria and reference models evaluated for the practice of re-designing a socio-technical system with operator participation?

Table 62: Research questions and their corresponding discussion section

11.1 The developed STS re-design approach – questions and problems

This discussion begins by aligning the research findings from Chapters 4 – 10 with RQ3 (Soc): What opportunities, problems, and questions arise (social and technical) in relation to the participatory re-design of the assembly production (socio-technical) system and why are they significant? The major questions and problems (phrased as needs) that arose in the re-design of the assembly production (socio-technical) system project align with each chapter, as outlined in Table 63.

Chapter	Questions	Problem
Chapter 4	*What* are the ethical considerations involved in the participatory (re-)design of a socio-technical system? *How* can they be operationalized in an industrial re-design project?	Need to invite/recruit participants, establish trust, and set mutual expectations
Chapter 5	*How* can the problem be defined in socio-technical system re-design? *What* is the re-design problem in the STS re-design project at hand?	Need for an emic problem for re-design
Chapter 6	*How* can a socio-technical system be modeled from operator participation and how does it benefit re-design? *What* is the socio-technical system model in the re-design project at hand?	Need to consider the existing socio-technical system in re-design, and need for re-design foci
Chapter 7	*How* do participants take action to co-design solution variants in STS re-design? *How* does the model of participant action(s) in collective creativity (in co-designing solution variants in STS re-design) compare with brainstorming?	Need to understand the participant actions in co-design and how this relates to co-designing solution variants
Chapter 8	*What* are the participants' detailed designs for the STS (assembly production system) re-design developed from collective creativity?	Need to understand the result of collective creativity and the differentiated designs
Chapter 9	*How* can the differentiated designs be evaluated in a before versus after socio-technical system model comparison?	Need to assess the re-design impact relative to the emic socio-technical system
Chapter 10	*How* do the participants evaluate their differentiated designs and ideas (Chapter 7 and 8) in terms of the emic problem (Chapter 5)?	Need to assess the re-design impact relative to the emic problem

Table 63: Alignment of the chapters, problems, and questions that arose in the re-design project

The questions and problems addressed in each chapter in Table 63 are significant because they directly relate to steps in the developed participatory approach (model and framework) for re-designing a socio-technical system.

11.2 The developed STS re-design approach – the model as demonstrated

This section aligns the research findings from Chapters 4 – 10 with RQ1:

- RQ1 (Soc): How can engaging socio-technical system operators as participants in re-designing an assembly production system develop an approach for re-designing socio-technical systems that operationalizes human value and potential?
- RQ1 (Eng): What is the re-design model to re-design an assembly production (socio-technical) system with stakeholder participation, human value, and human potential?
- RQ1 (DRM): How can the practice of re-designing a socio-technical system with operator participation be demonstrated and defined?

Chapters 4 – 10 each model a step in the overall model of the participatory approach for re-designing a socio-technical system, as practiced in the industrial re-design project at hand and demonstrated in the re-design of an assembly production system with 32 participants. Since a design model is "an abstraction that simulates a phenomenon," (Chakrabarti and Blessing, 2014b, p. 13; Sonalkar et al., 2014, p. 69), it is fitting to organize the evidence of the re-design project into a model that simulates the phenomenon of re-designing a socio-technical (assembly production) system that was experienced. Chapters 4 – 10 each conclude with a summary of their step in an IDEF0 model, per Table 64.

Chapter	Step in the developed participatory approach for re-designing a STS	Corresponding IDEF0 model
Chapter 4	Ethical considerations for participation	Figure 29
Chapter 5	Emic problem analysis	Figure 39
Chapter 6	Emic system modeling	Figure 55
Chapter 7	Collective creativity	Figure 72
Chapter 8	Differentiated designs	Figure 86
Chapter 9	Emic system evaluation	Figure 93
Chapter 10	Emic problem evaluation	Figure 98

Table 64: IDEF0 model summary for each chapter (step in the developed participatory approach for re-designing a STS)

Together, the IDEF0 models in Table 64 define each step in the model of the participatory approach for re-designing a socio-technical system developed in this dissertation, per Figure 100.

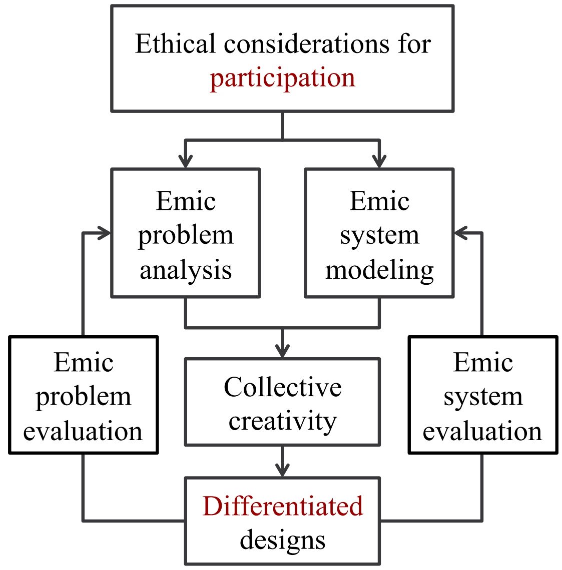


Figure 100: The developed model for re-designing a socio-technical system

Since the model in Figure 100 integrates several models (for each step, consisting of developed mechanisms), the approach and practice for re-designing a socio-technical system developed in this dissertation is considered a framework. The framework begins with participation, which is continued through each step of Figure 100, and proceeds to differentiation (hence the title of this dissertation – from participation to differentiation).

The particular aspects of operationalizing human value and potential for RQ1 (Soc) and RQ1 (Eng) are evaluated in §11.4, specifically in relation to points (5) and (11). The IDEF0 models for each step in Figure 100 (per Table 64) are further analyzed in relation to RQ2 and RQ3 in the next section.

11.3 The developed STS re-design approach – inputs, outputs, constraints, and mechanisms in the model

This section first summarizes the inputs, outputs, and outcomes of the steps in the STS re-design model (from the individual IDEF0 models for each step, as summarized in Table 64). Next, the mechanisms and constraints of the steps in the STS re-design model are summarized. Together, they address the first part of RQ2 (Eng) and RQ3 (Eng):

- RQ2 (Eng) first part: What are the inputs and mechanisms to re-design an assembly production (socio-technical) system with stakeholders?

- RQ3 (Eng): What are the constraints, outputs, and outcomes to re-design an assembly production (socio-technical) system with stakeholders?

The IDEF0 model inputs, mechanisms, outputs, and constraints illustrate how the success criteria, reference models, and support were developed (RQ2 DRM) and evaluated (RQ3 DRM).

- RQ2 (DRM): What success criteria, reference models, and support are relevant to the practice of re-designing a socio-technical system with operator participation? How are the success criteria, reference models, and support developed?
- RQ3 (DRM): How are the success criteria and reference models evaluated for the practice of re-designing a socio-technical system with operator participation?

The inputs, outputs, and outcomes for the steps in the STS re-design model (from the individual IDEF0 models of each step in Chapters 4 – 10, as summarized in Table 64) are presented in Table 65. The numbers in Table 65 correlate with the steps in the STS re-design model by chapter numbers (4- Ethical considerations for participation; 5- Emic problem analysis; 6- Emic system modeling; 7- Collective creativity; 8- Differentiated designs; 9- Emic system evaluation; and 10- Emic problem evaluation).

Input, output, and/or outcome	Input to step in Chapter #	Output or outcome of step in Chapter #
Professional engineering code of ethics	4	
Research ethics principles	4	
Participatory design ethical questions	4	
Trust between participants and researchers/engineers and foundation for data reliability	5, 6, 7, 8, 9, 10	4
Mutual expectations for participants, researchers/engineers, and the company		4
Informed and voluntary participants (with their experience operating the current socio-technical system)	5, 6, 7, 8, 9, 10	4
Emic problem reference model and emic problem statement, including:	7, 10	5
Web of participant concerns (26)		5
Re-design foci (8 critical issues and 3 themes of process, layout, and training)	7, 10	5
Emic system reference model including: fuzzy cognitive maps (collective interview, observation, and integrated)	9	6
Re-design foci (4 themes of process, layout, training and differentiated design) and their supporting clauses	7	6
Solutions (with details but not necessarily fully detailed) that are assessed and contextualized/differentiated (process, layout, and training solutions)	8, 10	7
Differentiated designs (re-designed process; re-designed layout; quality "double-check" system; training checklist)	9, 10	8
Assessed impact of the differentiated designs on system behaviour (r) and function (cycle time reduction)		9
Assessed impact of the differentiated designs on the emic problem (success criteria including 8 critical issues) and emic problem space (plotted success criteria, -49.19% change from before to after)		10
Ranked designs in terms of importance		10
Evaluated participation (voice and say)		10
Identified future opportunities for re-design (applications and features of a good design)		10

Table 65: Summary of inputs, outputs, and outcomes in the model for re-designing a STS

Table 65 highlights the importance of trust and participants in the model for re-designing a socio-technical system.

The mechanisms and constraints for the steps in the STS re-design model (from the individual IDEF0 models of each step, as summarized in Table 64) are summarized in

Table 66. The developed investigative approach mechanisms are fundamental contributions of this dissertation to the body of research (as stated in §1.2).

Mechanisms developed in the re-design approach	Corresponding constraints	Research contribution per §1.2
Roadmap of ethical considerations for participation in STS re-design (Chapter 4, §4.4)	Risk management	IIIa, IIIb
An emic problem analysis investigative approach that utilizes graph theory and emic coding to analyze participant expressions (interviews) of the current and ideal socio-technical system (in Chapter 5 §5.1 and in evaluation in Chapter 10)	Time	Ia, IIIb
An emic socio-technical system modeling investigative approach that utilizes fuzzy cognitive mapping and statistical analysis to analyze participant knowledge (interviews) and practice (observation) in operating the socio-technical system (in Chapter 6, §6.2 and in evaluation in Chapter 9, §9.1)	Time	Ib, Ic, IIIb
A model of OPEN collective creativity that explains participant actions in relation to opportunities, problems, enquiries/questions, and needs and how they relate to developing concept and detail ideas (Chapter 7, §7.4)	Common availability of participants	II, IIIb

Table 66: Summary of the mechanisms and constraints in the re-design approach

The inputs in Table 65 and mechanisms in Table 66 also relate to RQ2 (Soc) and the latter part of RQ2 (Eng):

- RQ2 (Eng) latter part: How do these [inputs and mechanisms] compare to traditional engineering inputs and mechanisms?
- RQ2 (Soc): How do alternative (e.g. social science) and existing engineering design knowledge, practice, theory, methods, tools, techniques, etc. mis/align with this participatory re-design and why?

To address these questions, the methods, tools, and techniques are first evaluated with respect to the mechanisms (Table 66) in the STS re-design approach in each respective chapter.

The first developed mechanism is a roadmap of ethical considerations for participation in socio-technical system re-design. This roadmap utilizes research ethics principles common to social science research and an engineering code of conduct common to engineering practice. The roadmap aligns these into ethical considerations/questions in a socio-technical system re-design project. The result in research is (potentially) recruited participants; the result in design is (potentially) invited participants. For a more detailed account of how this investigative approach was developed, please see Chapter 4.

The second developed mechanism is the emic problem analysis investigative approach for socio-technical system re-design. This approach utilizes emic (insider) coding from social science practice and is indicative of the qualitative methodology from social science. The coding is performed relative to interviews, which are common to social science, but are also a general human factors method in engineering. These codes are plotted in phases of the process, which align with process mapping. Process mapping is common to industrial engineering, but for this developed investigative approach it is drawn from interview rather than observation. This coding is combined with graph theory and analyzed with matrix algebra, which are commonly utilized in engineering. For a more detailed account of how this investigative approach was developed, and its particular references, please see Chapter 5.

The third developed mechanism is the emic STS modeling investigative approach for socio-technical system re-design. This approach utilizes fuzzy cognitive mapping to code and analyze the data. Fuzzy cognitive mapping is an emerging approach in engineering (Papageorgiou, 2014), previously used in the social sciences (e.g. Axelrod's (1976) *Structure of Decision Making: The Cognitive Maps of Political Elites*). Interviews are coded as well as an observation operation model, the latter with an adaptation of the coding technique. Both observation and interviews are human factors methods and social science research methods, but this does not mean that they have the same meaning to both groups. For example, the combination of the two methods is considered field study in social science research (as is the case here), in which a contextual approach is valued – coming to know the participants in their natural environment, which includes gathering a range of data. In human factors, observations may be short and they usually focus on quantitative data gathered in relation to specific purposes. The intent behind the method is also critical. In a field study approach in relation to a qualitative methodology, the intent is to understand the situation from the participant perspective (as is the case here). The observation operational model is constructed from statistical analyses that are common in manufacturing and industrial engineering (e.g. with respect to Six Sigma methodology). For a more detailed account of how this investigative approach was developed, and its particular references, please see Chapter 6.

The fourth developed mechanism is the model of OPEN collective creativity. This model is grounded in the participants' actions in co-design, a form of participatory design, and is applied here in relation to co-designing solution variants. Participatory design has been utilized and advocated in engineering and originated in computer science. Aspects of this model that relate to a collaborative approach to conflict and inquiry refer to social science research. Aspects described in relation to design, such as creativity and brainstorming, are inter-disciplinary. The model's focus on synthesis and analysis is fundamental to engineering and systems design methodologies. For a more detailed account of how this investigative approach was developed, and its particular references, please see Chapter 7.

For all of these mechanisms, the participants are an input and are also a part of the mechanism. For example, the data is from the participants; the actions are theirs; and the emic perspective is theirs. Participants are more common to social science research than to traditional engineering research, so participants are a feature of the developed approach for re-designing a socio-technical system that integrates the social science approach with the engineering design approach.

11.4 The developed STS re-design approach – relating to the literature

To further address RQ2 (Soc) an alignment is drawn between the major research findings and the alignment of social science and existing engineering design knowledge, practice, and theory. This is accomplished by relating the major research findings in the IDEF0 models in the developed participatory approach for socio-technical system design (per Table 64) to the literature review. Specifically, the major research findings are related to the 11 critical conditions for developing an approach for re-designing a socio-technical system, which were synthesized from the literature review. These 11 critical conditions (from §2.7) are:

(1) Ask what the standard elements or well-mastered technology are to base a socio-technical system re-design on;
(2) Be enriched with knowledge of socio-technical systems and at best socio-technical (inter-disciplinary) acumen in relation to engineering design methodology;
(3) Integrate socio-technical systems theory into a re-design approach for socio-technical systems, to develop an approach that is cognizant of the nature of socio-technical systems and consequently fundamentally relatable to different types of socio-technical systems;
(4) Identify, clarify, develop, and organize re-design activities across the scope of re-designing a socio-technical system; and
(5) Operationalize human value and potential.
(6) Align design with human values; this alignment directly connects to the technology and manufacturing literature calls for further attention to human values and human aspects in manufacturing system design and operation;
(7) Regard work as a crux to connect the social and technical aspects of the socio-technical system and means to operationalize human potential in collective human activity;
(8) Respect people as purposeful beings, which challenges the prescriptive technology orientation, and regards assembly operators as unique individuals rather than interchangeable parts of the system;
(9) Consider the core purpose of the system that connects the parts of the system -- "to be economically productive" in assembly production systems;
(10) Arrange the parts of the socio-technical system in the dimensional domain; and
(11) Regard human potential highly and develop it.

The following major findings from the IDFE0 models (evidence in Chapters 4 – 10) are considered:

(A) Emic web of problem analysis (emic problem reference model)

(B) Emic codes from problem analysis (emic problem reference model criteria, including the 8 critical issues)

(C) Investigative approach for emic problem analysis

(D) FCM maps of system modeling and analysis (emic system reference model, including the observation operational model)

(E) Emic concepts from system modeling and analysis (emic system reference model criteria, including observation operational model criteria)

(F) Investigative approach for emic system modeling (including the observation operational model investigative approach)

(G) OPEN collective creativity model

(H) Evaluation of reference models (emic system and problem evaluation)

(I) Participants and participation

(J) Differentiation in outcomes from re-design activities (e.g. emic problem statement, re-design foci and their supporting clauses, re-designs)

(K) Operationalized ethical considerations for participation

(L) Roadmap of ethical considerations for participation

The 11 considerations for developing an approach for re-designing a socio-technical system are aligned with major findings A – L in the following cognitive map (Figure 101).

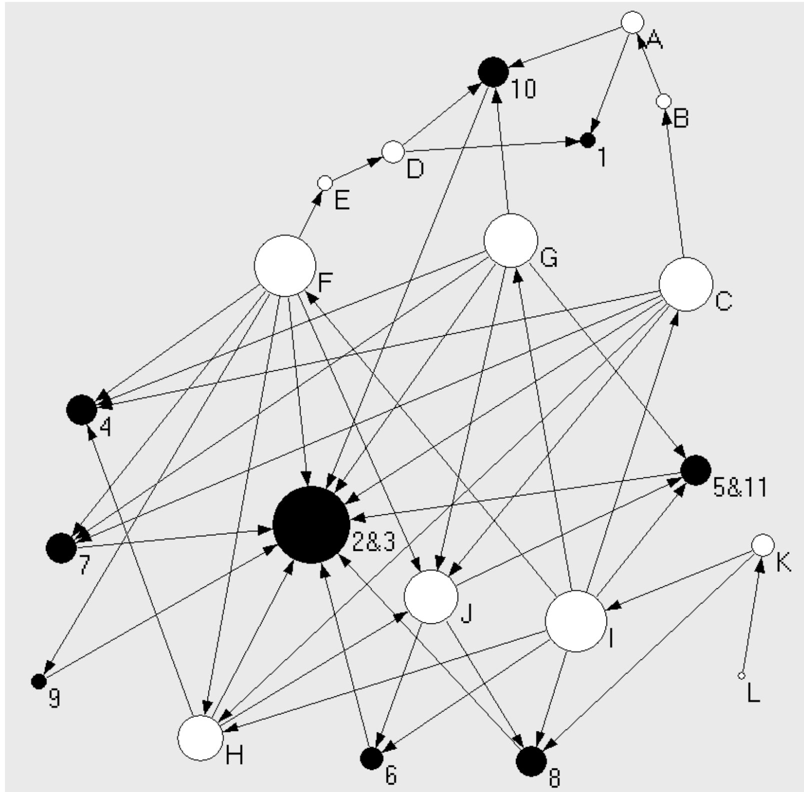


Figure 101: Cognitive map relating the literature and research findings, theoretical reference model (black nodes – from the literature; white nodes – from the IDEF0 models)

In Figure 101, the major findings from the IDEF0 models (summarized in Table 64) are shown as white nodes. The 11 considerations from the literature are shown as black nodes. The size of the node is representative of its centrality (the sum of the number of vectors entering and exiting the circle). The size of the node, therefore, indicates how inter-connected the node is and shows how important a finding or consideration is to the developed re-design approach. The relationships in Figure 101 are further explained relative to the 11 considerations as follows.

(1) Ask what the standard elements or well-mastered technology are to base a socio-technical system re-design on

The emic problem web (A) that is comprised of the emic codes from problem analysis (B from C) is a visual representation of the "web of technology" (1) that Franklin (1999) described in relation to the industrial context. The emic problem web and the emic codes directly contribute to the re-design foci that orient the re-design (i.e. they become the input to collective creativity).

The fuzzy cognitive maps (D) that arise out of the emic system modeling and analysis (E from F) identifies standard elements (1) as concepts (cause and effect concepts) that are related by linkages into a fuzzy cognitive map, which is another form of representation of the "web of technology" (1) that Franklin (1999) described in relation to the industrial context. The fuzzy cognitive map analysis directly contributes to the synthesis of re-design foci and tasks that orient the re-design (i.e. they become the input to collective creativity).

(4) Identify, clarify, develop, and organize re-design activities across the scope of re-designing a socio-technical system

The developed investigative approaches and models (C, F, G, and H) identify, clarify, and develop re-design activities (4) of problem analysis, system modeling and analysis, concept and detail ideation with OPEN actions in collective creativity, and evaluation of the re-designs and re-design experience. These activities are organized (4) as phases in the re-design approach (Figure 100).

(5) Operationalize human value and potential and (11) Regard human potential highly and develop it

Participation (I) operationalizes human value (5) and regards human potential highly (11) in participant voice and say, participants feeling heard, and participatory decision-making (post-survey responses). Participation (I) also operationalizes human value (5) and regards human potential highly (11) in the investigative approaches (C, F, H) and model of OPEN collective creativity (G). In the approaches that utilize general human factors methods (observation and interview – C, F, and H), human value is operationalized by the designers/researchers who conduct the method in relation to the participants (socio-technical system operators) and within the socio-technical system. In the model of OPEN collective creativity (G) with co-design, human value is operationalized by the participants (socio-technical system operators) in relation to the socio-technical system and with the designers who facilitate the method. The OPEN collective creativity model (G) also develops human potential (11) through mutual learning in co-design and through collective creativity in acknowledging individualism and social plurality. The differentiation (J) that results from the investigative approaches (C, F, and H) and OPEN collective creativity model (G) is evidence of the operationalization of human value and potential (5) in the outcomes of the mechanisms, which reflect a regard for human potential (11) in the re-design impact.

(6) Align design with human values; this alignment directly connects to the technology and manufacturing literature calls for further attention to human values and human aspects in manufacturing system design and operation;

Similarly to the alignment for considerations 5 and 11, participation (I) aligns design with human values (6). Participation (I) is established from operationalized ethical considerations (K) from the developed roadmap of ethical considerations (L). The ethical principles ground participation in the principles of respect for persons, concern for welfare, and justice (human values). Participation leads directly to the investigative approaches (C, F, and H) and OPEN collective creativity model (G) into differentiated outcomes from the re-design activities, including re-designs (J). These differentiated re-designs (J) also align design with human values (6) through the values inherent in the differentiated designs (e.g. fairness, flexibility, decision-making, etc.). The nature of differentiation, a design that "applies to us" in the words of a participant, was evidenced in the emic problem statement, the re-design foci #4 from the emic system modeling, the contextualization in collective creativity, and the post-survey evaluation that directly asked participants to score if the new design "applies to us." In other words, aligning design with human values (6) moves full-circle in the developed re-design approach, from participants in participation (I), through the re-design activities, to differentiated designs (J) and their evaluation.

(7) Regard work as a crux to connect the social and technical aspects of the socio-technical system and means to operationalize human potential in collective human activity

The investigative approaches for emic problem analysis (C) and emic system modeling (F), and the model of OPEN collective creativity (G) regard work as a crux to connect the social and technical aspects of the system (7). The interview questions in C and F directly ask participants to describe their work as well as the process in the socio-technical system, which operationalizes each participant's potential to contribute shared knowledge to collective problem analysis and collective system analysis. The model of OPEN collective creativity engages inclusive specialization of work roles, which operationalizes each participant's potential to take OPEN actions in direct collective human activity (creativity).

(8) Respect people as purposeful beings, which challenges the prescriptive technology orientation, and regards assembly operators as unique individuals rather than interchangeable parts of the system;

Participation (I) and operationalized ethical considerations (K) are directly aimed to respect people as purposeful beings (8) through informed and voluntary consent, inclusion principles, etc. Differentiation in the outcomes from the re-design activities, such as the differentiated re-designs, directly challenges the notion of prescriptive technology that requires compliance or standardization. Differentiation has a sense of compassion between socio-technical operators, by not only tolerating difference but moreover by directly valuing it. This speaks to respecting people as purposeful beings (8), as individuals, and with respect for context.

(9) Consider the core purpose of the system that connects the parts of the system -- "to be economically productive" in assembly production systems;

The investigative approach for emic system modeling (F), particularly the observation operational model, centrally considers the core purpose of the socio-technical (assembly production) system (9). The investigative approach in the industrial re-design project related complexity analysis to cycle time variation for both the pre- and post-designs. Cycle time represents the transformation of inputs into outputs, which is a simplistic yet direct representation of economic productivity in the assembly production (socio-technical) system.

(10) Arrange the parts of the socio-technical system in the dimensional domain

The emic web of problem analysis and reference model (A) is one representation of the parts of the socio-technical system in the dimensional domain (10), the domain of the industrial assembly production system in the re-design project (§3.4). The FCM maps of emic system modeling (the emic system reference model, D), including the observation operational model, are another representation of the parts of the socio-technical system in the dimensional domain (10). The evaluation of both of these reference models (G) also highlights changes in the arrangement of the parts of the socio-technical system in the dimensional domain (10) relative to the re-design intervention (reflecting pre- and post-conditions).

(2) Be enriched with knowledge of socio-technical systems and at best socio-technical (inter-disciplinary) acumen in relation to engineering design methodology; and (3) Integrate socio-technical systems theory into a re-design approach for socio-technical systems, to develop an approach that is cognizant of the nature of socio-technical systems and consequently fundamentally relatable to different types of socio-technical systems;

As noted from the initial literature review and synthesis of the 11 conditions (§2.7), the conditions 6-11 are from socio-technical systems theory so they correlate directly with conditions (2) and (3). The investigative approaches (C, F, and G) and the model of collective creativity (H) are inter-disciplinary (2). The investigative methods (C, F, and G) and the model of collective creativity (H) can also be related generally to socio-technical systems (3) through the 10 linkages of alignment between C, F, G, and H and socio-technical system theory considerations (6-11).

Together, the model of the developed socio-technical re-design approach (Figure 100) and its alignment with the 11 considerations define a framework for re-designing a socio-technical system that engages participants and operationalizes human value and potential (RQ1 (Soc); RQ1 (Eng)), as demonstrated in the re-design project (RQ1 (DRM)). In particular, the alignment between the model of the socio-technical re-design approach and considerations 5, 6, 8, and 11 outlines how human value and human potential is operationalized. With this alignment, the framework for re-designing socio-technical systems contributes the following to the body of literature:

- To the engineering re-design approaches literature (§2.1) -- A re-design model and framework for socio-technical systems that utilizes the fundamental concept of re-design based on standard elements and technology (1) for socio-technical systems in comparison to technical artefacts (2) by integrating socio-technical systems theory (3, 6-11) across a range of re-design activities (4);
- To the socio-technical and system engineering design methodology and methods literature (§2.2 and §2.5) – A re-design approach that relates socio-technical systems theory (3, 6-11) to the re-design of socio-technical systems utilizing co-design and general human factors methods to operationalize human value (5);
- To the socio-technical systems theory and manufacturing design literature (§2.3) – The application of socio-technical systems theory (3, 6-11) in relation to re-designing an assemble-to-order system; and
- To the manufacturing design and re-design techniques and approaches literature (§2.4) – a model and framework for re-designing a socio-technical system (such as a production system) to operationalize human value and potential (5) with STS theory (3, 6-11) featuring differentiation (versus standardization).

The boundaries and limitations related to the developed model and framework for re-designing a socio-technical system are evaluated in the following section on trustworthiness and validation, which includes a section on transferability/extend-ability.

11.5 The developed STS re-design approach – trustworthiness and validation

In qualitative research, trustworthiness is established with the following criteria that are related to validation in a quantitative approach in Table 67.

Criteria	Definition	Qualitative Approach	Quantitative Approach
Truth value	Confidence in findings and context in which the study was undertaken	Credibility	Internal validity
Applicability	Degree to which the findings can be applied to other contexts	Transferability	External validity
Consistency	If the inquiry was replicated, would the findings be the same?	Dependability	Reliability
Neutrality	Freedom from bias	Confirmability	Objectivity

Table 67: Trustworthiness criteria (based on (Krefting, 1991; Shenton, 2004))

Each of the criteria in Table 67 is discussed in the subsequent sections. In relation to each criterion, it's important to note the epistemological difference between qualitative versus quantitative research methodology. In a quantitative, or positivist, research methodology the researcher believes in objective knowledge that lies beyond the participants and the researcher strives to get to it, to then share it with others. In qualitative methodology, the researcher believes that the participants reveal knowledge to the researcher and the researcher strives to see if s/he can see what the participants see, to then help others to see it. This dissertation research is grounded in the qualitative methodology with grounded theory and PD (a form of action research); each step of the participatory approach for STS re-design is oriented from the emic (insider/participant/ STS operator) perspective. Therefore, the qualitative aspects of the criteria in Table 67 are primarily discussed in the subsequent sections. Since mixed methods have also been used in this dissertation, some of the analytical techniques (e.g. statistical analysis) do lend themselves to discussion on validity as well.

11.5.1 Truth value in the research and the STS re-design approach

Truth value has been established in this research in several aspects. The prolonged and varied field experience undertaken contributes to confidence in the findings and context. This research study took place over the course of 24 months in the industrial environment of the assembly production system. The research also involved a variety of design and research methods: interview, questionnaire, survey, observation, and co-design events. This range of design and research methods contributed to a significant number of primary sources of evidence that were analyzed at various stages of the research (interview transcripts; observation notes; questionnaires; surveys; co-design event reflection notes; participant reflection notes; group discussion notes on chart paper; group discussion notes taken by a participant; event feedback forms; design artefacts; etc.). The observation random sampling consisted of 225+145 samples, collected over several months. Since one step of the developed re-design model flows into the next (e.g. the output of one step becomes an input to another) there is ongoing member checking. Researcher reflexivity in writing reflections took place throughout the course of the research. The research ethics, outlined in detail in Chapter 4, also contributes substantially to the credibility of the data by establishing trust with the participants through the operationalization of the research ethics principles (respect for persons, concern for welfare, and justice). This substantially contributes to the management of any concerns related to data reliability. In addition, the investigative methods developed involve redundancy in coding in the emic problem analysis coding and the fuzzy cognitive mapping coding (for emic system modeling and the OPEN collective creativity model). For example, the redundancies in the participant general action codes in the OPEN collective creativity model were captured. As a result of these various conditions, the developed research demonstrates significant evidence for established truth value.

11.5.2 Transferability in the research and the STS re-design approach

Transferability has been established in this research in several aspects. Background data on the industrial context in terms of the technical, social, and participant aspects has been provided in detail (§3.4). This information includes production type, production volumes, assembly component combinations and variety, layout, participant work roles, process map, and participant demographics on age, sex, education, and visible minority. The participant data has also been compared to the broader manufacturing population data, which highlights the commonality between the two groups. Additional chapters provide further information on the context, e.g. Chapter 6 provides information on the number of assembling tasks, picking tasks, etc. This rich description of context enables subsequent researchers, engineers, and designers to compare this context with other contexts to assess the relation between contexts and the associated applicability of these research findings to other contexts. For all of the developed investigative methods, models, and framework the research and design methods have been outlined in detail in Chapters 4 – 10, with the test instruments included in the appendices. The before and after comparisons of the reference models also demonstrates a degree of generalizability for those developed investigative approaches. The roadmap of ethical considerations utilizes international research ethics principles, which also contributes to transferability. To fully understand the transferability of the re-design approach developed here to other contexts, it needs to be tested with other types of STSs. The rich description of context, methods, and investigative approaches will help in these future comparisons. For these future comparisons, it is also important to note the assumptions in the developed investigative approaches, models, and framework, per Table 68.

Developed investigative approaches, models, and framework	Assumptions
Investigative approach for emic problem analysis	Available participants; a process exists; there is a quiet meeting area for the interviews with a closed door; and there is time to perform the interviews, coding, and analysis.
Investigative approach for emic STS modeling	Available participants; the process is observable; the process transforms inputs into outputs; this transformation can be measured (timed); statistical test assumptions are not violated; there is a relationship between the process inputs, outputs, and the workers that varies in relation to a work strategy; there is time to perform the interviews, observations, coding, and analysis.
Model of OPEN collective creativity	Available participants; the participants will agree to respecting one another; participants will express some degree of openness to experimenting; events will be conducted in the work environment (e.g. meeting room and production environment); confidentiality cannot be ensured due to the social and open environment; and there is a mutual time that can be arranged for the participants to participate.
Roadmap of ethical considerations	Risk can be managed; the company agreements between researchers/designers and the company officials will be upheld; and researchers/designers will abide by the commitments they make with the participants.
Developed model and framework for re-designing a socio-technical system	Participation is possible; available participants; a before condition exists; all phases are carried out per the model from the emic perspective; and the other assumptions outlined for each of the mechanisms for the constituent phases (previously stated).

Table 68: Assumptions in the developed investigative approaches, models, and framework

The assumptions in Table 68 contribute to the limitations of the research and the developed investigative approaches, models, and framework. In general, it is also critical to note that the assembly production system, with which the re-design approach was developed, is a socio-technical system archetype as discussed in the introduction (Chapter 1). The develop re-design approach relates fundamentally to socio-technical systems theory, which has been generalized into other contexts. The mappings of the socio-technical systems theory considerations (6-11) are also directly aligned with the developed re-design approach (§11.4), which also helps to explain the generalizability of the developed re-design approach from the assembly production system context to other socio-technical system contexts. Potential contexts wherein the developed approach for re-designing socio-technical systems could be utilized could involve the growing service industry (e.g. in healthcare systems) and additional manufacturing systems. The participants also express ideas for how the re-design approach could be extended to other contexts in Chapter 10. As a result of these various conditions, the developed research demonstrates evidence for transferability/extend-ability that can be further tested in subsequent research.

11.5.3 Dependability in the research and the STS re-design approach

Dependability has been established in this research in several aspects. The research utilizes several overlapping data collections methods. For example, the pre-interview transcripts are evaluated in both the emic problem analysis and emic system modeling investigative approaches. Within the emic problem analysis investigative approach, several interviews (8 here) are analyzed and compared with emic coding into the emic problem web. Within the emic system modeling investigative approach, the same 8 interviews are analyzed and compared with FCM coding, codes are merged, and the adjacency matrices are merged into integrated fuzzy cognitive maps. Both the emic problem analysis and emic system modeling involve redundant coding (e.g. in the FCM analysis in emic system modeling, there were 218 linkages in the initial interview coding with 161 unique linkages; there were 247 codes in the initial interview coding with 120 codes after merging). Both the emic problem analysis and emic system modeling reveal the same re-design foci: process, layout, training, and differentiated design (“applies to us”). The interview data is also compared with the observation data, which are drawn from 10 unique data sets in the pre-observation and 8 unique data sets in the post-observation. The utilization of the investigative approaches in the pre- and post-re-design conditions also tests the investigative approaches, their reference models, and success criteria with respect to two design conditions. The OPEN collective creativity model is developed with several forms of overlapping evidence – observation notes, reflections taken immediately after the event, group notes written on chart paper during the event, design artefacts that the participants produced, and participant notes including reflections and observations. The fuzzy cognitive mapping coding with respect to this analysis also codes redundant concepts and linkages, further contributing to dependability. The OPEN model was consistent across the co-design settings (production area and meeting room); with two non-identical groups of participants; with different foci of process, layout, and training; and in the use of both discussion and kinesthetic learning methods. For each step in the developed model for re-designing a STS, their investigative approaches are provided in detail in Chapters 4 – 10 and are demonstrated in the industrial re-design project, which help these steps to be repeated in other socio-technical system contexts. The post-survey in emic problem evaluation only had 7 participants (which is not high for a survey), but this was not the only form of evaluation since emic system evaluation was also performed with post-observation. As a result of these various conditions, the developed research demonstrates significant evidence for established dependability.

11.5.4 Confirmability in the research and the STS re-design approach

Confirmability has been established in this research in several aspects. First, confirmability is supported by the establishment of truth value and applicability (Lincoln and Guba, 1985) through the in-depth methodological description of the research (Chapter 3) and the in-depth investigative approach descriptions in Chapters 4 – 10, including the research and design tests instruments in the appendices. This enables the research to be scrutinized. It is also worth noting here my bias as the researcher. I began this research with the belief that human potential, human value, and human development are worthwhile goals and ought to be explored in re-designing manufacturing systems and in engineering design. I did not have a particular hypothesis about how these aspects could be materialized or operationalized, only that they were worthwhile to explore for their ethical value and for the sake of compassion. This belief took root in me in my manufacturing experience, particularly in my experience as a manufacturing engineer and as a manager in a not-for-profit manufacturing professional society. My hope in this research was to truly engage in inquiry and see where the research questions might lead. As a result of these various conditions, the research developed demonstrates significant evidence for established confirmability.

This research establishes trustworthiness through the evidence provided in relation to truth value (§11.4.1), transferability (§11.4.2), dependability (§11.4.3), and confirmability (§11.4.4). These points are summarized in Table 69.

Criterion	Qualitative approach	Quantitative approach	Examples in the study
Truth value Confidence in findings and context in which the study was undertaken	Credibility	Internal validity	•Ethical considerations – trust and data reliability •Observation random sampling (226+145) •Coding merging and redundancy •Member checking •Length of study 24 months
Applicability Degree to which the findings can be applied to other contexts	Transferability	External validity	•Description of context of the study •Detailed methodology, methods, and investigative approaches •Emic problem and system reference models for comparison •Relation to STS theory •Stated assumptions in each phase of the STS re-design approach
Consistency If the inquiry was replicated, would the findings be the same?	Dependability	Reliability	•Overlapping data collection methods •Redundancy in coding •Emic problem and system analysis common re-design foci •Merged coding and integrated models
Neutrality Freedom from bias	Confirmability	Objectivity	•Detailed methodology and analysis •Grounding in data/evidence •Stated researcher bias and inquiry

Table 69: Summary of trustworthiness and validation in the research study (in relation to criteria by (Krefting, 1991; Shenton, 2004))

12 Conclusions, limitations, and future work

This dissertation identifies a shortcoming in the current literature on engineering re-design methodology: the existing re-design methodologies are predominantly oriented towards technical artefacts and not socio-technical systems. These existing methodologies are not directly transferable to socio-technical systems, which differ from technical artefacts in the way that workers operate the system in collective activity. This limitation inhibits engineers from fulfilling their responsibilities for re-designing socio-technical systems, which is especially central to the practice of industrial engineering.

In response, this dissertation develops a model and framework for re-designing a socio-technical system, which integrates socio-technical systems theory with engineering design methodology. This framework is developed with design research methodology and grounded theory -- grounded in the practice of re-designing an assembly production system (a socio-technical system archetype) with 32 participants in a range of work roles. The steps in the developed model for re-designing a socio-technical system are ethical considerations for participation; emic problem analysis; emic system modeling; collective creativity; differentiated designs; emic system evaluation; and emic problem evaluation. Several of these steps are supported by mechanisms developed within this dissertation: a roadmap of ethical considerations for participation; an investigative approach for emic problem analysis; an investigative approach for emic system modeling; and a model of OPEN collective creativity. These mechanisms support the developed model for re-designing a socio-technical system as a framework that moves from participation to differentiation.

The developed framework for re-designing a socio-technical system operationalizes human value and considers the critical significance of socio-technical system operators through the following, in (1) Direct participation in all steps and mechanisms of the developed re-design model; (2) Grounding the re-design approach in the emic (insider/participant/socio-technical system operator) perspective; (3) In OPEN collective creativity and mutual learning; and in (4) Differentiated re-designs that participants can claim "applies to us."

This developed framework for re-designing a socio-technical system provides a basis for comparison with other system and engineering design methodologies and methods. Future research needs to test its transferability with other types of socio-technical systems.

12.1 Limitations and future work

This dissertation develops a framework for re-designing a socio-technical system, developed with an assembly production system. Though the assembly production system is a socio-technical system archetype, other types of socio-technical systems have unique challenges and opportunities for consideration in a re-design approach. This is certainly true in order to be consistent in honouring a spirit and practice of differentiation. The developed re-design model and framework, therefore, need to be tested with other types of socio-technical systems in future research. In the same vein, it is important to outline the limitations of the steps within the developed model for re-designing a socio-technical system as follows, to understand the limits of its application and how future research questions can test these limits.

Limitations and future work with respect to ethical considerations for participation

The roadmap of ethical considerations for participation was developed in line with research ethics principles, which align with the context of research but may present difficulties in industrial contexts. For example, designers in industrial contexts do not have research ethics boards with whom to consult with questions, concerns, and problems. As a result, future research questions include: What obstacles exist when operationalizing the developed ethical considerations with other socio-technical systems and industrial contexts? What courses of action can a designer take when s/he encounters obstacles in managing risk in an industrial re-design project (e.g. economic risk as identified in Chapter 4)? What other mechanisms exist or can be constructed to support ethical considerations and practice in socio-technical system re-design? What other methods of building trust between designers and socio-technical system operators can be operationalized in re-design? These research questions will provide a more in-depth understanding of how to establish ethical considerations and a basis of trust between designers and participants in re-designing a socio-technical system with participation.

Limitations and future work with respect to emic problem analysis and emic problem evaluation

The investigative approach for emic problem analysis analyzes participant interview transcripts, and in particular evaluates responses to the current and ideal assembly process and associated work. This approach assumes that there is a process, which surfaces the question: How can the developed emic problem analysis approach be re-envisioned in situations that do not have a central process? In addition, the largest emic code in the pre-interview problem analysis was limited room and space, which participants ranked neutral in the post-survey. This was a constraint in the re-design project. Correspondingly, future research questions include: Are constraints usually positioned peripherally with a large magnitude of occurrence in emic problem analysis? Could this type of investigative approach be utilized as an indicator for major constraints that are affecting the system, and could their magnitude indicate cause for a systemic change to influence this constraint? These research questions will help to understand how emic problem analysis can further be adapted and utilized to guide the re-design of a socio-technical system.

Limitations and future work with respect to emic system modeling and emic system evaluation

Since the emic system modeling approach utilizes interviews, similar questions arise. The observation operational model also brings new conditions. In a socio-technical system with significant variety in work, such as the assemble-to-order system studied, the observation period can be extensive in order to observe a range of interactions. This can contribute to substantial effort and time required of the designer/researcher. Correspondingly, what other participatory means are there for measuring the primary function of the socio-technical system? Meanwhile, the time that the designer or researcher spends in observation is significant to his/her understanding of the system being re-designed. This experience can contribute to emergent insights, such as seeing a pattern or noting the significance of something that is different. It might be possible to strike a balance between reaping these benefits of observation while also not letting it be a bottleneck. Future research questions, therefore, include: What other re-design activities could co-occur with the observation? How can the observation be structured differently? As well, both of the emic problem analysis and emic system modeling investigative approaches relate to defining reference models that characterize the existing technology "based on standard elements or well-mastered technology" (Deneux and Wang, 2000, p.85). What other investigative approaches can be developed in line with this aim and how do they compare? How can they be related to the developed framework and model for socio-technical system re-design? These research directions will provide clarity for alternative means of emic system modeling in socio-technical system re-design, along with identifying adaptations and further significance in relation to the developed emic system modeling investigative approach.

Limitations and future work with respect to collective creativity

The OPEN collective creativity model was developed with groups of 7 to 9 participants. To challenge the significance of this condition in future research: How does this model vary with other sizes of groups? In this re-design project, three events were held with an average two-hour length. Is this the typical amount of time needed for these types of events? The co-design events were designed with a range of experiential and active learning methods, including discussion, kinesthetic learning, demonstration, reflection, writing, etc. What other experiential and active learning methods can be utilized? What effect do they have on the OPEN model of collective creativity? How can experiential learning models be related to the OPEN model? These events led to differentiated designs in the industrial re-design project. Is this outcome consistently indicative in other contexts and other participant groups that utilize the OPEN model? What is the long-term impact of differentiation on the socio-technical system? In the industrial re-design project, not all of the re-designs were implemented across the system and systematically, which prompts the following future research questions. How can implementation planning be integrated with co-design activities and collective creativity? What subsequent activities are needed to support full system re-design implementation? How can this implementation be studied in research when participation is dependent on voluntary consent that directly conflicts with company needs in some implementation efforts (e.g. in implementing training when a company needs all of the employees to be trained)? Also, can the OPEN model of collective creativity be utilized individually? What would be the similarities and differences in the OPEN model outcomes when utilized individually versus collectively? Could the OPEN model be taught to participants prior to a co-design event as a form of design sensitization? What would the outcomes be? How does the OPEN model compare with other creativity models in addition to brainstorming? These research directions will provide a more detailed understanding of the context and conditions of the OPEN model of collective creativity, to better understand its transferability and outcomes in relation to other socio-technical systems and participant groups.

Limitations and future work with respect to differentiated designs

The differentiated designs are an outcome of OPEN collective creativity and co-design events in this research. Future research can seek to better understand if differentiated designs are consistently an outcome of the OPEN collective creativity model and supporting co-design activities. This will require further testing of the OPEN collective creativity model in other contexts and applications, with additional participant groups and ideation purposes.

Limitations and future work with respect to the developed re-design model and framework for socio-technical system re-design

The methodology of this research is richly described in Chapter 3. This methodology can serve as a reference point for future research to ask: What other qualitative research methods can be utilized in studying the re-design of a socio-technical system? Ethnography and phenomenology might be two options of particular relevance, to further examine the experience of the socio-technical operators in relation to socio-technical system re-design. Additionally, the industrial context of this research study (in Chapter 3) also provides a basis for future research directions. What other measures of participant openness to experimenting can be related to the re-design model and framework and to new developments in socio-technical system re-design approaches? How critical is openness as expressed by participants to the re-design framework and model? What other aspects of individualism are important to socio-technical system re-design? In this study, participants expressed their age, sex, visible minority status, and education in anonymous questionnaires. Future research inquiries into these aspects, in relation to socio-technical system re-design, could examine their significance not only from the perspective of participants but also in relation to the researcher/designers. This re-design approach was developed with co-design, along with the general human factors and social science research methods of interview and observation. What other participatory design and human-centered design methods can be utilized in a socio-technical system re-design approach to operationalize human value and potential? How can these methods be related as adaptations, alternatives, or evolutions to/of the developed re-design model and framework? How would the inputs, outputs, and constraints differ? Most generally, how does the developed re-design framework and model compare in use in other socio-technical systems? These research directions will provide a comparative analysis between other approaches and applications in relation to the developed framework and model and the research findings presented in this dissertation.

12.2 Review of the dissertation contributions

The central problem addressed by this dissertation is how to develop an approach for re-designing a socio-technical system that:

- Integrates socio-technical systems theory and engineering design methodology;
- Utilizes the existing web of technology and standard elements in the socio-technical system (a reference model); and
- Operationalizes human value and potential across a scope of re-design activities.

To this aim, the re-design activities performed in the re-design project are based on the development of new, supporting investigative approaches and models. Synthesized, these new contributions are mechanisms in the seven steps in the developed model and framework for re-designing a socio-technical system: ethical considerations for participation; emic problem analysis; emic system modeling; collective creativity; differentiated designs; emic system evaluation; and emic problem evaluation.

For the ethical considerations step, a roadmap of ethical considerations was developed (Chapter 4). This roadmap was constructed by aligning international research ethics principles (respect for persons, concern for welfare, and justice) with a professional engineering code of ethics into critical questions for the participatory re-design of a socio-technical system. The roadmap operationalizes ethical principles into practices that create a basis of trust between designers and participants, in order to invite participants to engage in re-design and establish data reliability. The roadmap was operationalized in the industrial re-design project to recruit 32 participants into the research study and re-design activities.

For the emic problem analysis step, an investigative approach for emic problem analysis was developed (Chapter 5). The investigative approach codes participant interview transcripts into an emic problem web and reference model, with themes as re-design foci. The coding and web is analyzed with graph theory and adapted usability analysis to inform an emic problem statement and re-design success criteria in relation to emic problem analysis. In the re-design project, the re-design foci were process, layout, and training, which aligned with 8 critical issues (success criteria).

For the emic system modeling step, an investigative approach for emic system modeling was developed (Chapter 6). The investigative approach utilizes fuzzy cognitive mapping (FCM) to code interview transcripts and an observation operational model built from observations and inductive statistics. The coding results in fuzzy cognitive maps that are integrated as an emic system reference model, wherein re-design foci and clauses are built from the FCM overall cause, effect, and central concepts that reveal system behaviour, function, structure, and principles. In the re-design project, the re-design foci were process, layout, training, and differentiated design. Participants expressed the latter as a design that "applies to us."

For the collective creativity step, a model of OPEN collective creativity was developed (Chapter 7). The OPEN collective creativity model was built by using FCM to code and analyze participant actions in a co-design activity, involving solution variant ideation. This resulted in a non-linear model of collective creativity that centralizes OPEN actions (opportunities, problems, enquiries/questions, and needs) between concept and detail ideas, integrating problem solving and inquiry with collaboration. The developed model of OPEN collective creativity engages participants in transforming the re-design foci into differentiated, contextualized designs through synthesis and analysis.

For the differentiated designs step, the differentiated, contextualized designs from collective creativity (Chapter 7) are further detailed in co-design events (Chapter 8). In the re-design project at hand, the differentiated designs were grouped as a re-designed process, a re-designed layout, a quality “double-check” system, and a training checklist.

For the emic system evaluation step, the investigative approach for emic system modeling was used to compare the socio-technical system before versus after the re-design intervention (testing of the differentiated designs) (Chapter 9). This comparison was made using pre-observation (n=226) and post-observation (n=145) data. This analysis evaluates the impact of the re-design on the STS, as well as provides a new datum for future re-designs. In the re-design project, the observation operational model comparison highlighted an improved primary function of the assembly production system after the re-design intervention -- a mean cycle time reduction of -0.72 minutes/assembly (95% confidence interval, -1.04 to -0.40 minutes/assembly, n=18) from a paired t-test.

For the emic problem evaluation step, a survey was used to compare the emic problem before (as defined in Chapter 5) versus after the re-design intervention (differentiated designs) (Chapter 10). This analysis evaluates the impact of the re-design on the emic problem and evaluates the re-design experience, as well as provides a new datum for future re-designs. In the re-design project, the problem analysis comparison measured 13 emic problem success criteria before and after the re-design with a post-survey (n=7); when plotted on a radar chart, an overall 49.19% reduction in the emic problem space after the re-design intervention was found. In the post-survey (n=7), the participants also evaluated their participation in terms of having a voice and say (e.g. decision-making) for five criteria, with overall averages >3 (neutral) for each criteria and 74.3% of the scores agreeing or strongly agreeing with the participation statements.

Taken together, these seven steps comprise the model for re-designing a socio-technical system developed in this dissertation. Socio-technical systems theory and engineering design methodology are integrated in the mechanisms of each step, in the developed roadmap of ethical considerations for participation, investigative approaches for emic problem analysis and emic system modeling, and OPEN model of collective creativity. The existing web of technology is understood in emic problem analysis and emic system modeling reference models of the socio-technical system, which are utilized in collective creativity and evaluation of the emic problem and emic system model after a re-design intervention. Human value and potential is operationalized by participants in each step in the developed model for re-designing a socio-technical system, in the emic orientation of the model, in collective creativity and its mutual learning in the model, and in the differentiated design principle found throughout the model.

The purpose of this dissertation has been to surface a model and framework for re-designing a socio-technical system with socio-technical system operator participation, developed here in re-designing an assembly production system and socio-technical system archetype with 32 participants. This model and framework can serve as a basis for comparison with other system and engineering design methodologies and methods. Future research needs to further test the limitations of the developed framework (§10.1) and test its transferability with other types of socio-technical systems.

References

3M Six Sigma DMAIC Guide Book. (2005). London, ON: 3M Canada.

About IIE. (2015, May 24). Retrieved May 24, 2015, from https://www.iienet2.org/details.aspx?id=282

Ackoff, R., & Emery, F. (2005). *On Purposeful Systems: An Interdisciplinary Analysis of Individual and Social Behavior as a System of Purposeful Events*. London, UK: Aldine Transaction.

Ackoff, R. L., Magidson, J., & Addison, H. J. (2006). *Idealized Design: How to Dissolve Tomorrow's Crisis...Today* (1st ed.). Upper Saddle River, NJ: Pearson Prentice Hall.

Agyapong-Kodua, K., Darlington, R., & Ratchev, S. (2013). Towards the derivation of an integrated design and manufacturing methodology. *International Journal of Computer Integrated Manufacturing*, *26*(6), 527–539.

Alberti, P., Dejean, P.-H., & Cayol, A. (2007). How to assist and capitalise on a creativity approach: a creativity model. *CoDesign*, *3*(sup1), 35–44.

Alting, L. (1995). Life Cycle Engineering and Design. *CIRP Annals - Manufacturing Technology*, *44*(2), 569–580.

Angyal, A. (1972). *Foundations for a Science of Personality*. New York, NY: Penguin Books.

Appelbaum, S. H. (1997). Socio-technical systems theory: an intervention strategy for organizational development. *Management Decision*, *35*(6), 452–463.

Axelrod, R. (1976). *Structure of Decision: The Cognitive Maps of Political Elites*. Princeton, NJ: Princeton University Press.

Badham, R., & Couchman, P. (1996). Implementing Team-based Cells in Australia: A Configurational Process Approach. *Integrated Manufacturing Systems*, *7*(5), 47–59.

Badke-Schaub, P., Neumann, A., Lauche, K., & Mohammed, S. (2007). Mental models in design teams: a valid approach to performance in design collaboration? *CoDesign*, *3*(1), 5–20.

Baxter, G., & Sommerville, I. (2011). Socio-technical systems: From design methods to systems engineering. *Interacting with Computers*, *23*(1), 4–17.

Bhatta, S. R., & Goel, A. K. (2002). Design patterns and creative design. In A. Chakrabarti (Ed.), *Engineering Design Synthesis* (pp. 271–284). London, UK: Springer.

Bjerknes, G., & Bratteteig, T. (1988). The Memoirs of Two Survivors: Or the Evaluation of a Computer System for Cooperative Work. In *Proceedings of the 1988 ACM Conference on Computer-supported Cooperative Work* (pp. 167–177). New York, NY: ACM.

Blessing, L. T. M., & Chakrabarti, A. (2009). *DRM, a Design Research Methodology*. London, UK: Springer.

Bley, H., Reinhart, G., Seliger, G., Bernardi, M., & Korne, T. (2004). Appropriate Human Involvement in Assembly and Disassembly. *CIRP Annals - Manufacturing Technology*, *53*(2), 487–509.

Bødker, K., Kensing, F., & Simonsen, J. (2004). *Participatory IT design: designing for business and workplace realities*. Cambridge, MA: MIT Press.

Bonacin, R., Baranauskas, M. C. C., & Cecilia, R. M. (2003). Designing and Learning: Joining the Concepts in Work Practices. *Educational Technology & Society*, *6*(1), 3–8.

Boothroyd, G. (1982). *Design for assembly handbook*. Amherst, MA: Department of Mechanical Engineering, University of Massachusetts.

Boothroyd, G., & Alting, L. (1992). Design for Assembly and Disassembly. *CIRP Annals - Manufacturing Technology*, *41*(2), 625–636.

Boothroyd, G., & Dewhurst, P. (1986). *Product design for assembly*. Wakefield, RI: Boothroyd Dewhurst Inc.

Boothroyd, G., Dewhurst, P., & Knight, W. A. (2010). *Product Design for Manufacture and Assembly, Third Edition* (3 edition). Boca Raton, FL: CRC Press.

Britos Cavagnaro, L. (2013, July). *Frame the problem - empathize and define*. Presented at the Stanford University Design Thinking Action Lab MOOC, Online.

Byron, K. (2012). Creative reflections on brainstorming. *London Review of Education*, *10*(2), 201–213.

Campbell, J., & Moyers, B. (1988). *The Power of Myth*. New York, NY: Doubleday.

Carley, K., & Palmquist, M. (1992). Extracting Representing and Analyzing Mental Models. *Social Forces*, *70*(3), 601–636.

Chakrabarti, A. (Ed.). (2002). *Engineering Design Synthesis: Understanding, Approaches and Tools* (2002 edition). London, UK: Springer.

Chakrabarti, A., & Blessing, L. T. M. (Eds.). (2014a). *An Anthology of Theories and Models of Design*. London, UK: Springer.

Chakrabarti, A., & Blessing, L. T. M. (2014b). Theories and Models of Design: A Summary of Findings. In A. Chakrabarti & L. T. M. Blessing (Eds.), *An Anthology of Theories and Models of Design* (pp. 1–45). London, UK: Springer.

Checkland, P. (1999). *Systems Thinking, Systems Practice: Includes a 30-Year Retrospective* (1 edition). Chichester, UK: Wiley.

Checkland, P. (2000). Soft systems methodology: a thirty year retrospective Reproduced from Soft Systems Methodology in Action, John Wiley & Sons, Ltd., Chichester, 1999. *Systems Research & Behavioral Science*, *17*, 11–S58.

Checkland, P., & Scholes, J. (1990). *Soft Systems Methodology in Action*. Chichester, UK: John Wiley & Sons Ltd.

Cherns, A. (1978). The principles of sociotechnical design. In W. A. Pasmore & J. J. Sherwood (Eds.), *Sociotechnical systems: a sourcebook* (pp. 61–71). La Jolla: University Associates.

Cherns, A. (1989a). Principles of Socio-Technical Design. In E. Trist & M. Hugh (Eds.), *The Social Engagement of Social Science: A Tavistock Anthology* (Vol. 2: The Socio-Technical Systems Perspective, pp. 1–16). The Tavistock Institute of Human Relations. Retrieved from http://www.moderntimesworkplace.com/archives/archives.html

Cherns, A. (1989b). *The Social Engagement of Social Science: A Tavistock Anthology*. (E. Trist & M. Hugh, Eds.) (Vol. 2: The Socio-Technical Systems Perspective). The Tavistock Institute of Human Relations. Retrieved from http://www.moderntimesworkplace.com/archives/archives.html

Chism, N. V. N., Douglas, E., & Hilson Jr, W. J. (2010). Qualitative Research Basics: A Guide for Engineering Educators. *National Science Foundation 2008*.

Clancey, W. J. (1993). The knowledge level reinterpreted: Modeling socio-technical systems. *International Journal of Intelligent Systems*, *8*(1), 33–49.

Corbin, J. M., & Strauss, A. L. (2008). *Basics of qualitative research: techniques and procedures for developing grounded theory*. Los Angeles, CA: Sage Publications.

Coulibaly, A., Houssin, R., & Mutel, B. (2008). Maintainability and safety indicators at design stage for mechanical products. *Computers in Industry*, *59*(5), 438–449.

Cross, N. (Ed.). (1972). *Design Participation: Proceedings of the design research society's conference 1971*. London, UK: Academy editions.

Cross, N. (2008). *Engineering Design Methods: Strategies for Product Design* (4 edition). Chichester, UK: Wiley.

Daly, S., McGowan, A., & Papalambros, P. (2013). Using qualitative research methods in engineering design research. *DS 75-2: Proceedings of the 19th International Conference on Engineering Design (ICED13), Design for Harmonies, Vol.2: Design Theory and Research Methodology, Seoul, Korea, 19-22.08.2013*.

Definition of framework by Merriam-Webster. (2015). Retrieved May 23, 2015, from http://www.merriam-webster.com/dictionary/framework

Deming, W. E. (2000). *The New Economics for Industry, Government, Education* (2nd ed.). Cambridge, MA: The MIT Press.

Deneux, D., & Wang, X. H. (2000). A knowledge model for functional re-design. *Engineering Applications of Artificial Intelligence*, *13*(1), 85–98.

Dixon, J. R., & Poli, C. (1995). *Engineering design and design for manufacturing: a structured approach : text and reference for mechanical engineers*. Conway, MA: Field Stone Publishers.

Dixon, L. A., & Colton, J. S. (2000). A process management strategy for re-design: An Anchoring Adjustment approach. *Journal of Engineering Design*, *11*(2), 159–173.

Dong, A. (2004). Design as a Socio-Cultural Cognitive System. *DS 32: Proceedings of DESIGN 2004, the 8th International Design Conference, Dubrovnik, Croatia*, 1–8.

Dörner, D. (1994). Heuristik der Theorienbildung. *Enzyklopädie Der Psychologie*, *1*, 343–388.

Edwards, K. L. (2002). Towards more strategic product design for manufacture and assembly: priorities for concurrent engineering. *Materials and Design*, *23*(7), 651–656.

Ehn, P. (1988). *Work-oriented design of computer artifacts*. Umeå Universitet, Stockholm, Sweden.

Ellul, J. (1967). *The technological society*. New York, NY: Vintage Books.

Ellul, J. (1999). *The Technological Bluff*. Grand Rapids, MI: Wm. B. Eerdmans Publishing Co.

ElMaraghy, H. A., & ElMaraghy, W. H. (Eds.). (2006). *Advances in Design*. London, UK: Springer.

ElMaraghy, W. (2011). Future Trends in Engineering Education and Research. In G. Seliger, M. M. K. Khraisheh, & I. S. Jawahir (Eds.), *Advances in Sustainable Manufacturing* (pp. 11–16). Berlin, DE: Springer.

ElMaraghy, W., ElMaraghy, H., Tomiyama, T., & Monostori, L. (2012). Complexity in Engineering Design and Manufacturing. *CIRP Annals - Manufacturing Technology*, *61*(2), 793–814.

ElMaraghy, W. H., & Urbanic, R. J. (2003). Modelling of Manufacturing Systems Complexity. *CIRP Annals - Manufacturing Technology*, *52*(1), 363–366.

ElMaraghy, W. H., & Urbanic, J. (2004). Assessment of Manufacturing Operational Complexity. *CIRP Annals - Manufacturing Technology*, *53*(1), 401–406.

Emery, F. (1989a). Characteristics of Socio-Technical Systems. In E. Trist & H. Murray (Eds.), *The Social Engagement of Social Science: A Tavistock Anthology* (Vol. 2: The Socio-Technical Systems Perspective, pp. 1–31). The Tavistock Institute of Human Relations. Retrieved from http://www.moderntimesworkplace.com/archives/archives.html

Emery, F. (1989b). The Assembly Line: Its Logic and Our Future. In E. Trist & M. Hugh (Eds.), *The Socio-Technical Systems Perspective* (Vol. 2, pp. 1–19). The Tavistock Institute of Human Relations.

Emery, F. (1989c). The Nine Step Model. In E. Trist & M. Hugh (Eds.), *The Social Engagement of Social Science: A Tavistock Anthology* (Vol. 2: The Socio-Technical Systems Perspective, pp. 1–18). The Tavistock Institute of Human Relations. Retrieved from http://www.moderntimesworkplace.com/archives/archives.html

Engineers Canada. (2014). *2014 Canadian Engineering Accreditation Board Accreditation Criteria and Procedures* (p. 116). Retrieved from https://www.engineerscanada.ca/sites/default/files/2014_accreditation_criteria_and_procedures_v06.pdf

Faltings, B. (2002). FAMING: supporting innovative design using adaptation — a description of the approach, implementation, illustrative example and evaluation. In A. Chakrabarti (Ed.), *Engineering Design Synthesis* (pp. 285–302). London, UK: Springer.

Feibleman, J., & Friend, J. W. (1978). The Structure and Function of Organizations. In F. E. Emery (Ed.), *Systems Thinking* (Vol. 1). Harmondsworth, UK: Penguin Books.

Field Study | Usability Body of Knowledge. (2012). Retrieved April 8, 2015, from http://www.usabilitybok.org/field-study

Fiksel, J., & Wapman, K. (1994). How to design for environment and minimize life cycle cost. In *, 1994 IEEE International Symposium on Electronics and the Environment, 1994. ISEE 1994., Proceedings* (pp. 75–80).

Finger, S., & Rinderle, J. R. (2002). Transforming behavioural and physical representations of mechanical designs. In A. Chakrabarti (Ed.), *Engineering Design Synthesis* (pp. 303–317). London, UK: Springer.

Fisher, M., Jain, A., & MacDuffie, J. P. (1995). Strategies for Product Variety: Lessons from the Auto Industry. In *Redesigning the Firm* (pp. 116–154). Oxford, UK: Oxford University Press.

Franklin, U. M. (1999). *The Real World of Technology (CBC Massey Lectures series) Revised Edition* (2nd ed.). Toronto, ON: House of Anansi Press.

Fraser, K., Harris, H., & Luong, L. (2007). Team-based Cellular Manufacturing: A Review and Survey to Identify Important Social Factors. *Journal of Manufacturing Technology Management*, *18*(6), 714–730.

Frohlich, D. M., Lim, C. S. C., & Ahmed, A. (2014). Keep, lose, change: Prompts for the re-design of product concepts in a focus group setting. *CoDesign*, *10*(2), 80–95.

Glaser, B. G., & Strauss, A. L. (1967). *The Discovery of Grounded Theory: Strategies for Qualitative Research*. Chicago, IL: Aldine de Gruyter.

Gonçalves, M., Cardoso, C., & Badke-Schaub, P. (2014). What inspires designers? Preferences on inspirational approaches during idea generation. *Design Studies*, *35*(1), 29–53.

Government of Canada. (2010, December 7). The TCPS 2 Tutorial Course on Research Ethics (CORE) [Government]. Retrieved September 22, 2013, from http://pre.ethics.gc.ca/eng/policy-politique/initiatives/tcps2-eptc2/Default/

Hancock, D. R., & Algozzine, R. (2011). *Doing case study research: a practical guide for beginning researchers*. New York, NY: Teachers College Press.

Hanington, B., & Martin, B. (2012). *Universal Methods of Design: 100 Ways to Research Complex Problems, Develop Innovative Ideas, and Design Effective Solutions* (1.2.2012 edition). Beverly, MA: Rockport Publishers.

Hauschild, M. Z., Jeswiet, J., & Alting, L. (2004). Design for Environment — Do We Get the Focus Right? *CIRP Annals - Manufacturing Technology*, *53*(1), 1–4.

Hennink, M., Hutter, I., & Bailey, A. (2010). *Qualitative Research Methods*. London ; Thousand Oaks, CA: Sage Publications.

Hirtz, J., Stone, R. B., McAdams, D. A., Szykman, S., & Wood, K. L. (2002). A functional basis for engineering design: reconciling and evolving previous efforts. *Research in Engineering Design*, *13*(2), 65–82.

Hollnagel, E., & Woods, D. D. (2005). *Joint Cognitive Systems: Foundations of Cognitive Systems Engineering*. Boca Raton, FL: CRC Press, Taylor and Francis Group.

Horváth, I. (2014). What the Design Theory of Social-Cyber-Physical Systems Must Describe, Explain and Predict? In A. Chakrabarti & L. T. M. Blessing (Eds.), *An Anthology of Theories and Models of Design* (pp. 99–120). London, UK: Springer.

Hudspith, B., & Jenkins, H. (2001). *Teaching the Art of Inquiry*. Halifax, NS: Society for Teaching and Learning in Higher Education.

Hu, S. J., Ko, J., Weyand, L., ElMaraghy, H. A., Lien, T. K., Koren, Y., … Shpitalni, M. (2011). Assembly System Design and Operations for Product Variety. *CIRP Annals - Manufacturing Technology*, *60*(2), 715–733.

Hyer, N. L., Brown, K. A., & Zimmerman, S. (1999). A Socio-technical Systems Approach to Cell Design: Case Study and Analysis. *Journal of Operations Management*, *17*(2), 179–203.

Hyman, B. (1998). *Fundamentals of Engineering Design*. Upper Saddle River, NJ: Prentice Hall.

IDEO. (2011). *Human centered design toolkit*. [S.l.]: AuthorHouse.

Iversen, O. S., Halskov, K., & Leong, T. W. (2012). Values-led participatory design. *CoDesign*, *8*(2-3), 87–103.

Jing, N., & Lu, S. C.-Y. (2011). Modeling Co-construction Processes in a Socio-Technical Framework to Support Collaborative Engineering Design. *IEEE Transactions on Systems, Man, and Cybernetics, Part C: Applications and Reviews*, *41*(3), 297–305.

Jones, A., Artikis, A., & Pitt, J. (2013). The design of intelligent socio-technical systems. *Artificial Intelligence Review*, *39*(1), 5–20.

Juran, J. M. (1992). *Juran on Quality by Design: The New Steps for Planning Quality into Goods and Services* (Revised edition). New York, NY: Free Press.

Kelley, T., Littman, J., & Peters, T. (2001). *The Art of Innovation: Lessons in Creativity from IDEO, America's Leading Design Firm* (1 edition). New York, NY: Crown Business.

Kember, P., & Murray, H. (1988). Towards Socio-technical Prototyping of Work Systems. *International Journal of Production Research*, *26*(1), 133.

Kensing, F., & Blomberg, J. (1998). Participatory design: Issues and concerns. *Computer Supported Cooperative Work (CSCW)*, *7*(3-4), 167–185.

Kilmann, R. H., & Thomas, K. W. (1975). Interpersonal conflict-handling behavior as reflections of Jungian personality dimensions. *Psychological Reports*, *37*, 971–980.

Koren, Y. (2010). *The Global Manufacturing Revolution: Product-Process-Business Integration and Reconfigurable Systems*. Hoboken, NJ: Wiley.

Kosko, B. (1986). Fuzzy Cognitive Maps. *International Journal of Man-Machine Studies*, *24*, 65–75.

Kosko, B. (2014). Foreward. In E. I. Papageorgiou (Ed.), *Fuzzy Cognitive Maps for Applied Sciences and Engineering* (Vol. 54). Berlin, DE: Springer.

Koza, J. R. (2002). Automatic synthesis of both the topology and numerical parameters for complex structures using genetic programming. In A. Chakrabarti (Ed.), *Engineering Design Synthesis* (pp. 319–337). London, UK: Springer.

Krefting, L. (1991). Rigor in Qualitative Research: The Assessment of Trustworthiness. *The American Journal of Occupational Therapy*, *45*(3), 214–222.

Kumar, V. (2012). *101 design methods: a structured approach for driving innovation in your organization*. Hoboken, NJ: Wiley.

Kuo, T.-C., Huang, S. H., & Zhang, H.-C. (2001). Design for manufacture and design for "X": concepts, applications, and perspectives. *Computers & Industrial Engineering*, *41*(3), 241–260.

Laing, A. C. (2007). Effectiveness of a Participatory Ergonomics Intervention in Improving Communication and Psychosocial Exposures. *Ergonomics*, *50*(7), 1092–1109.

Laing, A., Frazer, M., Cole, D., Kerr, M., Wells, R., & Norman, R. (2005). Study of the Effectiveness of a Participatory Ergonomics Intervention in Reducing Worker Pain Severity Through Physical Exposure Pathways. *Ergonomics*, *48*(2), 150–170.

Lehto, M. R., & Landry, Steven J. (2013). *Introduction to human factors and ergonomics for engineers (2nd edition)*. Boca Raton, FL: CRC Press.

Leonard, D., & Rayport, J. (1997). Spark Innovation Through Empathic Design. *Harvard Business Review*, *75*(6 (November-December)), 102–113.

Liker, J., & Hoseus, M. (2008). *Toyota Culture: The Heart and Soul of the Toyota Way* (1 edition). New York, NY: McGraw-Hill.

Lincoln, Y. S., & Guba, E. G. (1985). *Naturalistic Inquiry*. Beverly Hills, CA: SAGE.

Lin, Y., & Zhang, W. J. (2004). Towards a novel interface design framework: function–behavior–state paradigm. *International Journal of Human-Computer Studies*, *61*(3), 259–297.

Lu, S. C.-Y., & Cai, J. (2001). A collaborative design process model in the sociotechnical engineering design framework. *AI EDAM*, *15*(01), 3–20.

Määttä, T. J. (2007). Virtual Environments in Machinery Safety Analysis and Participatory Ergonomics. *Human Factors and Ergonomics in Manufacturing*, *17*(5), 435–443.

Mathiassen, L. (1981). *System Development and System Development Method* (PhD. thesis, DAIMI PB-136, Computer Science). Arhus University, Denmark.

Matthews, B. (2009). Intersections of brainstorming rules and social order. *CoDesign*, *5*(1), 65–76.

Muller, M. J., & Kuhn, S. (1993). Participatory design. *Communications of the ACM*, *36*(6), 24–28.

Mumford, E. (2006). The story of socio-technical design: reflections on its successes, failures and potential. *Information Systems Journal*, *16*(4), 317–342.

Murakami, T. (2002). Retrieval using configuration spaces. In A. Chakrabarti (Ed.), *Engineering Design Synthesis* (pp. 229–243). London, UK: Springer.

Naumann, T., Tuttass, I., Kallenborn, O., & Königs, S. F. (2011). Social Systems Engineering - An Approach for Efficient Systems Development. *DS 68-4:*

Proceedings of the 18th International Conference on Engineering Design (ICED 11), Impacting Society through Engineering Design, Vol. 4: Product and Systems Design, Lyngby/Copenhagen, Denmark, 15.-19.08.2011.

Nielsen, J. (1994). *Usability engineering*. San Francisco, CA: Morgan Kaufmann Publishers.

Nof, S. Y., Wilhelm, W. E., & Warnecke, H.-J. (1997). *Industrial Assembly*. London, UK: Springer Science & Business Media, Chapman & Hall.

Norman, B. A., Tharmmaphornphilas, W., Needy, K. L., Bidanda, B., & Warner, R. C. (2002). Worker assignment in cellular manufacturing considering technical and human skills. *International Journal of Production Research*, *40*(6), 1479–1492.

Norman, D. A., & Draper, S. W. (1986). *User Centered System Design; New Perspectives on Human-Computer Interaction*. Hillsdale, NJ: L. Erlbaum Associates Inc.

O'Driscoll, M. (2002). Design for manufacture. *Journal of Materials Processing Technology*, *122*(2–3), 318–321.

One-Way ANOVA. (2015). Retrieved from http://support.minitab.com/en-us/minitab/17/Assistant_One_Way_ANOVA.pdf

Ong, A. (2003). The Social Construction of Technology. In E. B. Leonard (Ed.), *Women, technology, and the myth of progress* (pp. 13–26). Upper Saddle River, NJ: Prentice Hall.

Osborn, A. (1953). *Applied Imagination: Principles and Procedures of Creative Thinking* (1st edition). New York, NY: Scribner.

Ottens, M., Franssen, M., Kroes, P., & Van de Poel, I. (2004). Modeling engineering systems as socio-technical systems. *Systems, Man and Cybernetics, 2004 IEEE International Conference on*, *6*, 5685–5690.

Özesmi, U., & Özesmi, S. L. (2004). Ecological models based on people's knowledge: a multi-step fuzzy cognitive mapping approach. *Ecological Modelling*, *176*(1-2), 43–64.

Pahl, G., Beitz, W., Feldhusen, J., & Grote, K.-H. (2007). *Engineering Design: A Systematic Approach*. (K. Wallace & L. Blessing, Eds.). London, UK: Springer.

Palma-Mendoza, J. A., Neailey, K., & Roy, R. (2014). Business process re-design methodology to support supply chain integration. *International Journal of Information Management*, *34*(2), 167–176.

Panebianco, S., & Pahl-Wostl, C. (2006). Modelling socio-technical transformations in wastewater treatment—A methodological proposal. *Technovation*, *26*(9), 1090–1100.

Papageorgiou, E. I. (Ed.). (2014). *Fuzzy Cognitive Maps for Applied Sciences and Engineering* (Vol. 54). Berlin, DE: Springer.

Papageorgiou, E. I., & Salmeron, J. L. (2014). Methods and Algorithms for Fuzzy Cognitive Map-based Modeling. In *Fuzzy Cognitive Maps for Applied Sciences and Engineering* (pp. 1–28). Berlin, DE: Springer.

Pasmore, W. A. (1988). *Designing effective organizations: the sociotechnical systems perspective.* New York, NY: Wiley.

PEO. Professional Engineers Act, O.Reg. 941, O.Reg. 941 General R.R.O. 1990 § 77 Code of Ethics of the Association (Professional Engineers Ontario) 1–20 (2011).

Pilemalm, S., Lindell, P.-O., Hallberg, N., & Eriksson, H. (2007). Integrating the Rational Unified Process and participatory design for development of socio-technical systems: a user participative approach. *Design Studies*, *28*(3), 263–288.

Qian, L. (2002). Creative design by analogy. In A. Chakrabarti (Ed.), *Engineering Design Synthesis* (pp. 245–269). London, UK: Springer.

Rasmussen, J., Pejtersen, A. M., & Goodstein, L. P. (1994). *Cognitive systems engineering*. New York, NY: Wiley.

Reid, F. J. M., & Reed, S. E. (2005). Speaker-centredness and participatory listening in pre-expert engineering design teams. *CoDesign*, *1*(1), 39–60.

ReVelle, J. B. (2002). *Manufacturing Handbook of Best Practices: An Innovation, Productivity, and Quality Focus*. Boca Raton, FL: CRC Press.

Roberts, F. S. (1976). The questionnaire method. In *Structure of Decision: The Cognitive Maps of Political Elites* (pp. 333–342). Princeton, NJ: Princeton University Press.

Robertson, T., & Simonsen, J. (2013). Participatory Design: An Introduction. In *Routledge International Handbook of Participatory Design* (pp. 1–17). New York, NY: Routledge.

Robertson, T., & Wagner, I. (2013). Ethics: Engagement, Representation and Politics-in-action. In *Routledge International Handbook of Participatory Design* (pp. 64–85). New York, NY: Routledge.

Rolfsen, M., Ingvaldsen, J., & Hatling, M. (2012). Graphical Profiling of Team Working through Participatory Research. *Team Performance Management*, *18*(1/2), 27–40.

Ropohl, G. (1999). Philosophy of Socio-Technical Systems. *Society for Philosophy and Technology*, *4*(3), 1–7.

Rufe, P. D. (2002). *Fundamentals of manufacturing*. Dearborn, MI: Society of Manufacturing Engineers.

Sanders, E. B.-N., & Stappers, P. J. (2008). Co-creation and the new landscapes of design. *CoDesign*, *4*(1), 5–18.

Schneider, M., Shnaider, E., Kandel, A., & Chew, G. (1998). Automatic construction of FCMs. *Fuzzy Sets and Systems*, *93*(2), 161–172.

Sharma, R., & Gao, J. X. (2006). A knowledge-based manufacturing and cost evaluation system for product design/re-design. *The International Journal of Advanced Manufacturing Technology*, *33*(9-10), 856–865.

Shaw, B. G. (2010). A cognitive account of collective emergence in design. *CoDesign*, *6*(4), 225–243.

Shenton, A. K. (2004). Strategies for ensuring trustworthiness in qualitative research projects. *Education for Information*, *22*(2), 63–75.

Simonsen, J., & Robertson, T. (2013). *Routledge International Handbook of Participatory Design*. New York, NY: Routledge.

Smith, G. F. (1998). Idea-Generation Techniques: A Formulary of Active Ingredients. *The Journal of Creative Behavior*, *32*(2), 107–134.

Sonalkar, N., Jung, M., Mabogunje, A., & Leifer, L. (2014). A Structure for Design Theory. In A. Chakrabarti & L. T. M. Blessing (Eds.), *An Anthology of Theories and Models of Design* (pp. 67–81). London, UK: Springer.

Spinuzzi, C. (2005). The Methodology of Participatory Design. *Technical Communication*, *52*(2), 163–174.

Statistics Canada. (2011). *National Household Survey 2011 [Canada]* (Public Use Microdata File (PUMF): Individuals File). Ottawa, ON: Statistics Canada.

Suchman, L. (2007). *Human-Machine Reconfigurations: Plans and Situated Actions*. Cambridge, UK: Cambridge University Press.

Suchman, L. A. (1987). *Plans and Situated Actions: The Problem of Human-Machine Communication*. Cambridge, UK: Cambridge University Press.

Sundblad, Y. (2011). UTOPIA: Participatory Design from Scandinavia to the World. In J. Impagliazzo, P. Lundin, & B. Wangler (Eds.), *History of Nordic Computing 3* (pp. 176–186). Berlin, DE: Springer.

Sundin, A. (2003). Computer visualization and participatory ergonomics as methods in workplace design. *Human Factors and Ergonomics in Manufacturing*, *13*(1), 1–17.

Sundin, A., Christmanssona, M., & Larsson, M. (2004). A Different Perspective in Participatory Ergonomics in Product Development Improves Assembly Work in the Automotive Industry. *International Journal of Industrial Ergonomics*, *33*(1), 1–14.

Sutcliffe, A. G. (2000). Requirements analysis for socio-technical system design. *Information Systems*, *25*(3), 213–233.

Svihla, V. (2010). Collaboration as a dimension of design innovation. *CoDesign*, *6*(4), 245–262.

Tamura, Y., & Itoh, K. (1994). Performance-oriented architecture design/re-design methodology. In *, Proceedings of International Conference on Expert Systems for Development, 1994* (pp. 144–147).

Taylor, M. (2014, July). *The Power to Create - Transcript.pdf*. Presented at the RSA Lecture, London, UK. Retrieved from https://www.thersa.org/globalassets/pdfs/blogs/mt-transcript.pdf

The National Commission for the Protection of Human Subjects of Biomedical and Behavioral Research. (1979). *The Belmont Report: Ethical principles and guidelines for the protection of human subjects of research*. Washington, DC: United States Department of Health, Education, and Welfare. Retrieved from http://www.hhs.gov/ohrp/humansubjects/guidance/belmont.html

Townsend, V., Boulos, P., & Urbanic, R. J. (2014). An Ethical Roadmap for Engineering Participatory Design and Sociotechnical Participation: A Manufacturing Case Study. In *ASME 2014 International Mechanical Engineering Conference*. Montreal, QC. Retrieved from http://www.asmeconferences.org/Congress2014/TechnicalProgramOverview.cfm#11

Townsend, V., & Urbanic, J. (2012). A Consortium Leveraged Learning Network. In H. A. ElMaraghy (Ed.), *Enabling Manufacturing Competitiveness and Economic Sustainability* (pp. 580–585). Berlin, DE: Springer.

Townsend, V., & Urbanic, J. (2014). Complexity Analysis for Problem Definition in an Assemble-to-order Process: Engaging Emic and Etic Perspectives. *Procedia CIRP*, *17*, 201–206. DOI: 10.1016/j.procir.2014.01.079

Townsend, V., & Urbanic, J. (2015). A Case Study Measuring the Impact of a Participatory Design Intervention on System Complexity and Cycle Time in an

Assemble-to-Order System. In *Procedia Manufacturing*, 1, 134-145. DOI: 10.1016/j.promfg.2015.09.076

Trist, E. L., & Bamforth, K. W. (1951). Some Social and Psychological Consequences of the Longwall Method of Coal-Getting An Examination of the Psychological Situation and Defences of a Work Group in Relation to the Social Structure and Technological Content of the Work System. *Human Relations*, *4*(1), 3–38.

Trist, E., & Murray, H. (1993). *The Social Engagement of Social Science: A Tavistock Anthology. Volume 2: The Socio-Technical Perspective*. Philadelphia, PA: University of Pennsylvania Press.

Van den Bergh, J., Haesen, M., Luyten, K., Notelaers, S., & Coninx, K. (2008). Toward Multi-disciplinary Model-Based (Re)Design of Sustainable User Interfaces. In T. C. N. Graham & P. Palanque (Eds.), *Interactive Systems. Design, Specification, and Verification* (pp. 161–166). Berlin, DE: Springer.

Vermaas, P. E. (2014). Design Theories, Models and Their Testing: On the Scientific Status of Design Research. In A. Chakrabarti & L. T. M. Blessing (Eds.), *An Anthology of Theories and Models of Design* (pp. 47–66). London, UK: Springer.

Vermaas, P. E., Kroes, P., Van de Poel, I., Franssen, M., & Houkes, W. (2011). *A Philosophy of Technology From Technical Artefacts to Sociotechnical Systems*. Milton Keynes, UK: Morgan & Claypool.

Vink, P., Koningsveld, E. A. P., & Molenbroek, J. F. (2006). Positive Outcomes of Participatory Ergonomics in Terms of Greater Comfort and Higher Productivity. *Applied Ergonomics*, *37*(4), 537–546.

Vom Brocke, J., Recker, J., & Mendling, J. (2010). Value‐oriented process modeling: integrating financial perspectives into business process re‐design. *Business Process Management Journal*, *16*(2), 333–356.

Vujosevic, R., Raskar, R., Yetukuri, N. v., Jothishankar, M. c., & Juang, S.-H. (1995). Simulation, animation, and analysis of design disassembly for maintainability analysis. *International Journal of Production Research*, *33*(11), 2999.

What is framework? definition and meaning. (2015). Retrieved May 23, 2015, from http://www.businessdictionary.com/definition/framework.html

Whitten, J. L., & Bentley, L. D. (2007). *Systems analysis and design methods*. Boston, MA: McGraw-Hill/Irwin.

Wiendahl, H.-P., ElMaraghy, H. A., Nyhuis, P., Zäh, M. F., Wiendahl, H.-H., Duffie, N., & Brieke, M. (2007). Changeable Manufacturing - Classification, Design and Operation. *CIRP Annals - Manufacturing Technology*, *56*(2), 783–809.

Winograd, T., & Flores, F. (1986). *Understanding Computers and Cognition: A New Foundation for Design*. New York, NY: Intellect Books.

Wrightson, M. T. (1976). The documentary coding method. In *Structure of Decision: The Cognitive Maps of Political Elites* (pp. 291–332). Princeton, NJ: Princeton University Press.

Yurtseven, M. K., Buchanan, W. W., & Basak, M. (2009). Joint Cognitive System Design and Process Control. In *Portland International Conference on Management of Engineering Technology, 2009. PICMET 2009* (pp. 2256–2262).

Zendoia, J., Zapp, M., Agyapong-Kodua, K., Lohse, N., & Singh, M. (2013). Fundamentals of a co-design methodology for improving the performance of machine tools based on semantic representation. *International Journal of Computer Integrated Manufacturing*, *26*(8), 751–761.

Zhang, W. J., Lin, Y., & Sinha, N. (2011). On the function-behavior-structure model for design. *Proceedings of the Canadian Engineering Education Association (pp.1-8)*.

Zhao, B., & Steier, F. (1993). Effective CIM implementation using socio-technical principles. *Industrial Management*, *35*(3), 27.

Zhao, B., Verma, A., & Kapp, B. (1992). Implementing Advanced Manufacturing Technology in Organizations: A Socio-technical Systems Analysis. In *IEEE Engineering Management Conference, Managing in a Global Environment* (pp. 9–13). IEEE International.

Zussman, E., Kriwet, A., & Seliger, G. (1994). Disassembly-Oriented Assessment Methodology to Support Design for Recycling. *CIRP Annals - Manufacturing Technology*, *43*(1), 9–14.

Appendices

Appendix A Recruitment script

Hello, my name is Victoria Townsend and I'm a student at the University of Windsor studying my PhD in Manufacturing Systems. For my research, I'm interested in seeing how people in manufacturing can be involved in designing assembly processes and work and what impacts this might have on engineering design and the work, process, and system. For this research, I'm looking at investigating the assembly process here at the Company X as a case study.

Company X has not asked for this project or initiated it. It's a study that I've designed and approached Company X with. Participation in this research study is voluntary and free, and Company X has agreed that you can use paid work time to participate if you choose and there are no risks to employment. If you choose to participate, there would be three main phases for this research study:

1. Pre-interview and a questionnaire (about 30 minutes).
2. Participatory design of the X assembly process with other participants where we'd collectively analyze the process and work, look at opportunities and problems, create ideas and solutions, create prototypes of the designs, select and implement a design, and then monitor how well the design works. Because this part of the research would be a group event, I cannot ensure complete confidentiality in this specific phase but I can ensure that I will keep your information confidential in this phase and all phases of the research. This research would also involve me observing the X assembly process and your work in limited time periods (no more than an hour at a time). If I'm observing I will always inform you and confirm that I have your consent to observe. I estimate that the participatory design will take 4-5 months, with approximately 2.5-5 hours/week
3. Post-interview (about 30 minutes).

If you choose to participate in the study, you can withdraw at any time. You can also choose to withdraw your data within one week of any data collection point (e.g. after an interview). At the end of the study, I will make a presentation of the results here at the X.

Do you have any questions about the research study or about what would be involved in participation?

You are welcome to take time to decide if you'd like to participate. This is a letter of information and a consent form. If you're interested in participating, you can bring the consent form to me (I'll be in the office upstairs at the end of the hall) both today and tomorrow. If you are interested in signing the consent form right now you can also choose that too. If you have any questions at any time please feel free to contact me at [redacted] (as listed on the letter of information and consent form). Thank you for you time.

Appendix B Consent form

CONSENT TO PARTICIPATE IN RESEARCH

Title of Study: A Case Study of the Participatory Design of Work and Assembly Processes in a Manufacturing System

You are asked to participate in a research study conducted by **Victoria Townsend and Dr. Jill Urbanic**, from the **Faculty of Engineering** at the University of Windsor. The results of this study will contribute to the PhD dissertation of Victoria Townsend. Company X is an industrial partner of this research.

If you have any questions or concerns about the research, please feel to contact Victoria Townsend at [redacted]

PURPOSE OF THE STUDY

This study is designed is designed to investigate how people in manufacturing can be involved in designing assembly processes and work and what they think about it. It's also designed to explore what opportunities, questions, and problems may arise for a person, people, process, and manufacturing system and how this might influence assembly process and manufacturing system design. The focus of this study would be the X assembly process at the Company X.

PROCEDURES

If you volunteer to participate in this study, you will be asked to:
Participate in a questionnaire and pre-interview. This would take place in an office at the X and would be no longer than 30 minutes.

Participate in participatory design. This would include working in the X assembly production area at the X and taking part in problem definition, analysis, synthesis, and realization to re-design the process and work. This would take place across 4-5 months for approximately 2.5-5 hours per week.

Participate in observation. The observations would include observing the X assembly process and your work with in the production area at the X. This would take place across 4-5 months (and the time would be part of the estimated 2.5-5 hours per week).

Participate in a post-interview. This would take place in an office at the X and would be no longer than 30 minutes.

POTENTIAL RISKS AND DISCOMFORTS

There are no known physical or psychological risks or discomforts associated with this research. Employees who take part in this research study will be allowed to use paid work time to participate with no influence on their employment, so the potential for employment or financial risk has been mitigated. Since participatory design is like a group event, and other people in the production area of the X will be able to see the design work taking place, confidentiality and privacy cannot be guaranteed in this specific procedure of the research study. The researcher will keep all data and information confidential in all of the procedures.

POTENTIAL BENEFITS TO PARTICIPANTS AND/OR TO SOCIETY

By participating in this research, individuals have the opportunity to gain knowledge and information on the design of their work in the X assembly process by participating in the research, analysis, synthesis, implementation and monitoring of the manufacturing process and associated work. Consequently, there is the potential for participants to impact change relative to their work practices and the X assembly process. Participants may also benefit from empowerment with respect to their work while also learning new knowledge and skills related to participatory design. Through participation, participants will be able to contribute to an emerging area of engineering research and inform process and work design from their perspectives. This orientation towards understanding engineering design from the perspective of people is seldom found in engineering theory. Participants in this research can take an active role in defining this orientation.

COMPENSATION FOR PARTICIPATION
There is no compensation for participation.

CONFIDENTIALITY
Any information that the researchers obtain in connection with this study and that can be identified with you will remain confidential and will be disclosed only with your permission. The questionnaire is anonymous and the interviews and observations are coded. Since participatory design is like a group event, and other people in the production area of the X will be able to see the design work taking place, confidentiality and privacy cannot be guaranteed in this specific procedure of the research study. The researchers will keep all data and information confidential in all of the procedures. Electronic files will be encrypted and stored on a password-protected computer. Any interview audio files will be immediately transcribed, verified, and then destroyed. Participants may ask for a copy of their audio files within one week of the interview. Any physical documents or files will be stored in a locked box. All files will be destroyed by June 2015 by secure overwriting (electronic files) and shredding (physical files).

PARTICIPATION AND WITHDRAWAL
Participation in this research study is voluntary. A participant can withdraw at any time without consequences of any kind. A participant can also refuse to answer any questions that s/he does not want to answer and still remain in the study. A participant can withdraw his/her data for the questionnaire, pre-interview, and post-interview within one week. The data and information collected in the participatory design and observation is collected in a group setting, so individual data cannot be extracted. Choosing to participate in this research study, and choosing to withdrawal from this research study, will have no influence on an individual's employment now or in the future. Company X has confirmed this in a company letter of support.

FEEDBACK OF THE RESULTS OF THIS STUDY TO THE PARTICIPANTS
A summary of the research findings will be presented in a presentation at the Company X in the winter of 2014. At this time, summaries of the research findings will also be presented to attendees of the presentation with extra copies posted at the Company X.

SUBSEQUENT USE OF DATA
These data may be used in subsequent studies, in publications and in presentations.

RIGHTS OF RESEARCH PARTICIPANTS
If you have questions regarding your rights as a research participant, contact: Research Ethics Coordinator, University of Windsor, Windsor, Ontario, [redacted]

SIGNATURE OF RESEARCH PARTICIPANT/LEGAL REPRESENTATIVE
I understand the information provided for the study **"A Case Study of the Participatory Design of Work and Assembly Processes in a Manufacturing System**" as described herein. My questions have been answered to my satisfaction, and I agree to participate in this study. I have been given a copy of this form.

____
Name of Participant

______________________________________ ____________________
Signature of Participant Date

SIGNATURE OF INVESTIGATOR

These are the terms under which I will conduct research.

_____________________________________ ____________________
Signature of Investigator Date

Appendix C Letter of information

LETTER OF INFORMATION FOR CONSENT TO PARTICIPATE IN RESEARCH

Title of Study: A Case Study of the Participatory Design of Work and Assembly Processes in a Manufacturing System

You are asked to participate in a research study conducted by **Victoria Townsend and Dr. Jill Urbanic**, from the **Faculty of Engineering** at the University of Windsor. The results of this study will contribute to the PhD dissertation of Victoria Townsend. Company X X is an industrial partner of this research.

If you have any questions or concerns about the research, please feel to contact Victoria Townsend at [redacted]

PURPOSE OF THE STUDY

This study is designed is designed to investigate how people in manufacturing can be involved in designing assembly processes and work and what they think about it. It's also designed to explore what opportunities, questions, and problems may arise for a person, people, process, and manufacturing system and how this might influence assembly process and manufacturing system design. The focus of this study would be the X assembly process at the Company X.

PROCEDURES

If you volunteer to participate in this study, you will be asked to:
Participate in a questionnaire and pre-interview. This would take place in an office at the X and would be no longer than 30 minutes.

Participate in participatory design. This would include working in the X assembly production area at the X and taking part in problem definition, analysis, synthesis, and realization to re-design the process and work. This would take place across 4-5 months for approximately 2.5-5 hours per week.

Participate in observation. The observations would include observing the X assembly process and your work with in the production area at the X. This would take place across 4-5 months (and the time would be part of the estimated 2.5-5 hours per week).

Participate in a post-interview. This would take place in an office at the X and would be no longer than 30 minutes.

POTENTIAL RISKS AND DISCOMFORTS

There are no known physical or psychological risks or discomforts associated with this research. Employees who take part in this research study will be allowed to use paid work time to participate with no influence on their employment, so the potential for employment or financial risk has been mitigated. Since participatory design is like a group event, and other people in the production area of the X will be able to see the design work taking place, confidentiality and privacy cannot be guaranteed in this specific procedure of the research study. The researcher will keep all data and information confidential in all of the procedures.

POTENTIAL BENEFITS TO PARTICIPANTS AND/OR TO SOCIETY

By participating in this research, individuals have the opportunity to gain knowledge and information on the design of their work in the X assembly process by participating in the research, analysis, synthesis, implementation and monitoring of the manufacturing process and associated work. Consequently, there is the potential for participants to impact change relative to their work practices and the X assembly process. Participants may also benefit from empowerment with respect to their work while also learning new knowledge and skills related to participatory design. Through participation, participants will be able to contribute to an emerging area of engineering research and inform process and work design from their perspectives. This orientation towards understanding engineering design from the perspective of people is seldom found in engineering theory. Participants in this research can take an active role in defining this orientation.

COMPENSATION FOR PARTICIPATION

There is no compensation for participation.

CONFIDENTIALITY

Any information that the researchers obtain in connection with this study and that can be identified with you will remain confidential and will be disclosed only with your permission. The questionnaire is anonymous and the interviews and observations are coded. Since participatory design is like a group event, and other people in the production area of the X will be able to see the design work taking place, confidentiality and privacy cannot be guaranteed in this specific procedure of the research study. The researchers will keep all data and information confidential in all of the procedures. Electronic files will be encrypted and stored on a password-protected computer. Any interview audio files will be immediately transcribed, verified, and then destroyed. Participants may ask for a copy of their audio files within one week of the interview. Any physical documents or files will be stored in a locked box. All files will be destroyed by June 2015 by secure overwriting (electronic files) and shredding (physical files).

PARTICIPATION AND WITHDRAWAL

Participation in this research study is voluntary. A participant can withdraw at any time without consequences of any kind. A participant can also refuse to answer any questions that s/he does not want to answer and still remain in the study. A participant can withdraw his/her data for the questionnaire, pre-interview, and post-interview within one week. The data and information collected in the participatory design and observation is collected in a group setting, so individual data cannot be extracted. Choosing to participate in this research study, and choosing to withdrawal from this research study, will have no influence on an individual's employment now or in the future. Company X Inc. has confirmed this in a company letter of support.

FEEDBACK OF THE RESULTS OF THIS STUDY TO THE PARTICIPANTS

A summary of the research findings will be presented in a presentation at the Company X in the winter of 2014. At this time, summaries of the research findings will also be presented to attendees of the presentation with extra copies posted at the Company X.

SUBSEQUENT USE OF DATA

These data may be used in subsequent studies, in publications and in presentations.

RIGHTS OF RESEARCH PARTICIPANTS

If you have questions regarding your rights as a research participant, contact: Research Ethics Coordinator, University of Windsor, [redacted]

SIGNATURE OF RESEARCH PARTICIPANT/LEGAL REPRESENTATIVE

I understand the information provided for the study **"A Case Study of the Participatory Design of Work and Assembly Processes in a Manufacturing System**" as described herein. My questions have been answered to my satisfaction, and I agree to participate in this study. I have been given a copy of this form.

SIGNATURE OF INVESTIGATOR

These are the terms under which I will conduct research.

____________________________________ ____________________
Signature of Investigator Date

Appendix D Consent for audio taping

Consent for Audio Taping

Title of the Study:
A Case Study of the Participatory Design of Work and Assembly Processes in a Manufacturing System

I understand that my participation in this interview is voluntary and that I am free to withdraw at any time by leaving the interview. I also understand that my name and the information that I share in this interview will be kept confidential. The audio file and electronic transcription of this interview will be filed by a code, encrypted, and stored on a password-protected computer. I understand that I have one week from today's date to withdraw the data and information that I share in this interview from the research study.

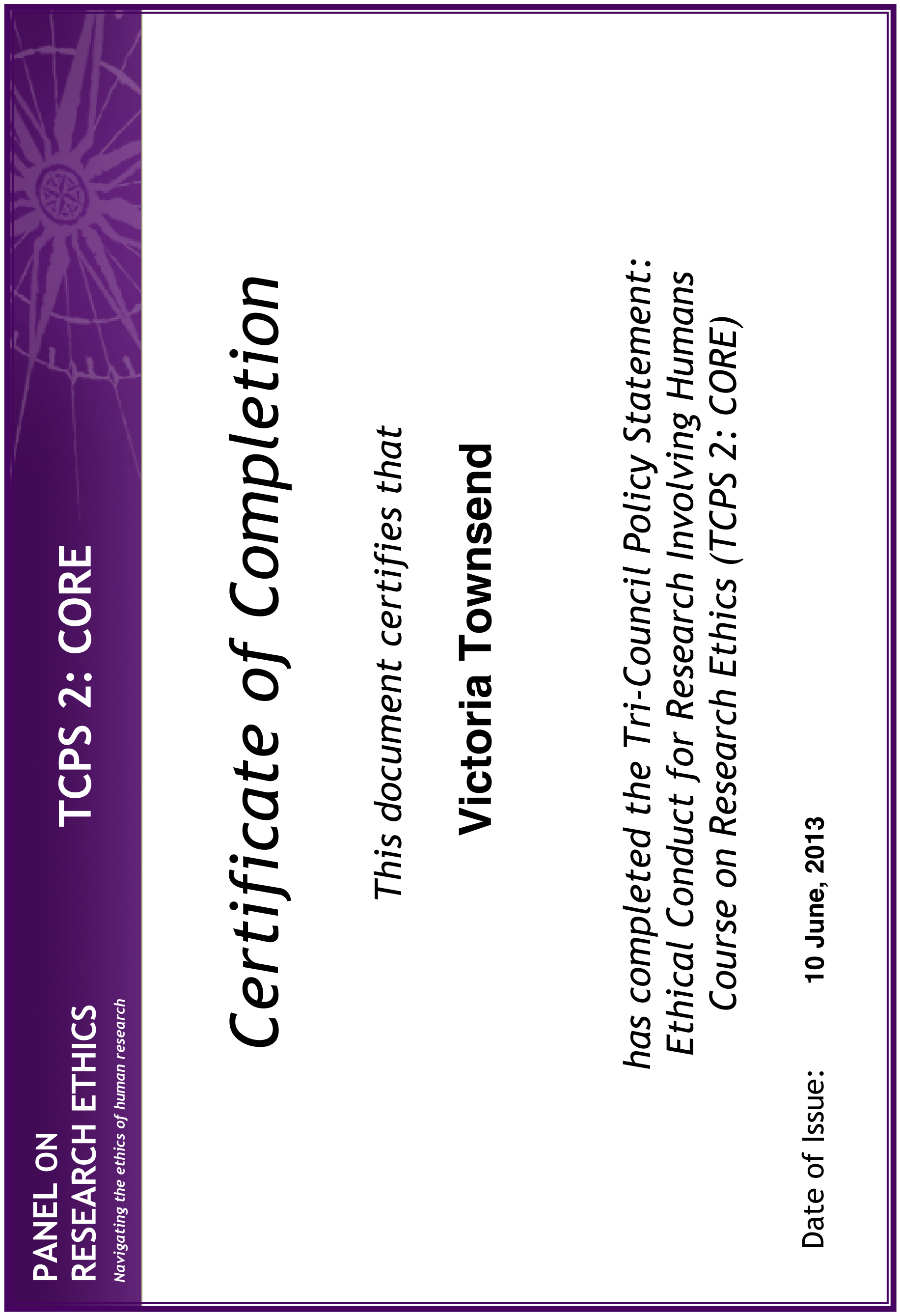
I consent to the audiotaping of this interview for the research study named above.

____
Date

____
Participant Name, Printed

____
Participant Signature

Appendix E Tri-council research ethics certificate


PANEL ON
RESEARCH ETHICS
Navigating the ethics of human research

TCPS 2: CORE

Certificate of Completion

This document certifies that

Victoria Townsend

has completed the Tri-Council Policy Statement: Ethical Conduct for Research Involving Humans Course on Research Ethics (TCPS 2: CORE)

Date of Issue: **10 June, 2013**

Appendix F Demographic questionnaire

The purpose of the demographic questionnaire is to better understand the sample population aspect of generalizability regarding this research and case study. The questionnaire, or survey, organizes a comparison between data on the sample population of people participating in this research study and the general manufacturing population data ("Census of Canada: Special Interest Profiles," 2006). It should be noted that as of June 2013, the 2011 census data was not yet public.

Demographic questionnaire script

This is the Demographic Questionnaire. The purpose of this Demographic Questionnaire is to gather information about the sample population of people taking part in this research study (including yourself) relative to the manufacturing population as a whole. This will help to understand the context of the research study. You can choose to withdraw your data within one week of completing this questionnaire. You can also refuse to answer any questions that you don't want to answer and still remain in the interview. At any time during this research study you can withdraw without any consequences of any kind. Do you have any questions at this time? …[Answer Questions].

If you'd like to complete this Demographic Questionnaire, you can write your answers on the paper and then seal your answers in this envelope. I won't open the envelope until the end of the study, and I will open all the envelopes at the same time, so this ensures that your answers remain anonymous. Would you like to complete this demographic questionnaire? [Participants will then choose to complete or forego the Demographic Questionnaire].

Demographic questionnaire

1. Age:

	15 to 24
	25 to 34
	35 to 44
	45 to 54
	55 to 64
	65 to 74

2. Gender:

	Male
	Female
	Other

3. Please check the following statement(s) on education that apply to you, and complete the sentence (*) if applicable.

	No schooling completed
	Some high school completed, no diploma or certificate
	High school graduation certificate or equivalent
	Other trades certificate or diploma
	Registered apprenticeship certificate
	College, CEGEP, or non-University certificate or diploma *Majored in:
	University certificate or diploma below bachelor level *Majored in:
	University bachelor's degree *Majored in:
	University certificate or diploma above bachelor's degree *Majored in:
	University graduate degree (Master's, PhD, or professional schooling) *Majored in:
	Other (please describe):

4. Please check the box below if one or more of the following visible minorities applies to you.

	Chinese, South Asian, Filipino, Latin American, Southeast Asian, Arab, West Asian, Korean, Japanese, another visible minority not indicated, or multiple visible minorities.

Appendix G Pre-interview

Pre-interview script and questions

The researcher will use the following script to ask the interview questions. The researcher may ask the participant to clarify or elaborate on a point if it is unclear, and in this respect the interview questions are semi-structured.

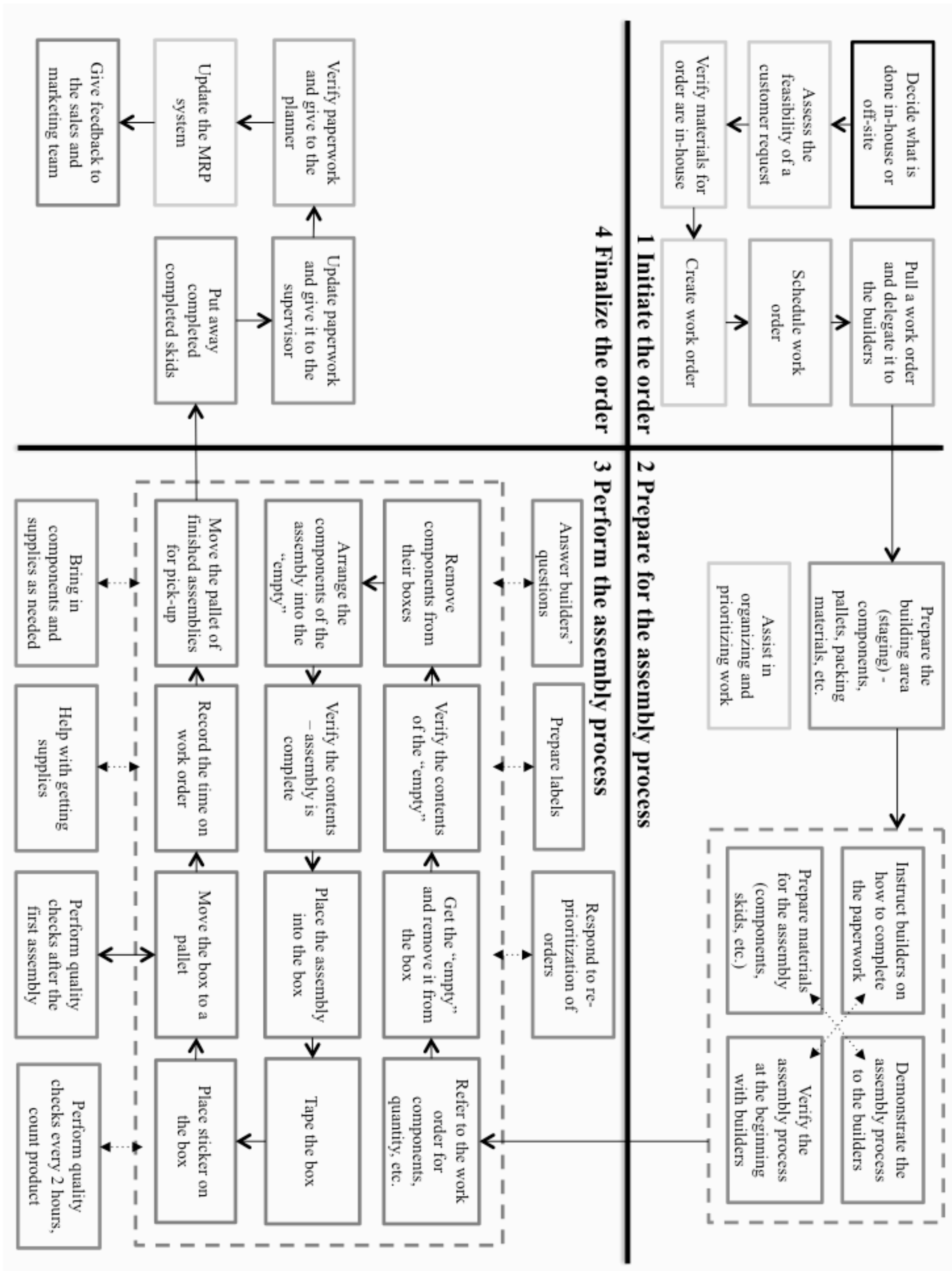
Before we begin the interview, I'll share a brief overview of the reasons for asking these interview questions. This interview is designed to help inform the participatory design of the X assembly process here at the X. This is part of my research into participatory design of manufacturing processes and systems, which is part of my PhD research at the University of Windsor. The interview questions ask about your perspectives on three main things: the context of the research study, the X assembly process, and your work with the X assembly process. If at any time you have a question, please feel free to ask. I'm happy to answer any questions. You can choose not to answer a question and proceed to the next question. You can also choose to withdraw from the interview and still participate in the study. At any time you can also withdraw from the research study. Do you have any questions before we begin? …The first question is…

1. How many years have you worked at the X?
2. In addition to your current role, do you have additional experience in manufacturing in other industries or roles?
3. Do you have past experience with participating in design, in manufacturing or another setting?
4. How would you describe the current X assembly process?
5. How would you describe your work with the current X assembly process?
6. How would you describe an ideal X assembly process?
7. How would you describe your ideal work with an ideal X assembly process?
8. How would you complete the following sentence? At the X, experimenting is…
9. Why do you work for the X Company?
10. Through your participation in this research study, is there anything that you would especially like to experience and participate in?
11. Through your participation in this research study, is there anything that you would not like to experience or to participate in?
12. Is there anything else that you'd like to comment on, or information that you'd like to share, with respect to this research study?

Thank you very much for participating in this interview. Do you have any questions for me? If you have any questions later, please feel free to ask me. I will be here at the X for the next [couple of days] and you can also contact me by email. My email address is listed on the Information Letter. Thank you and have a great day!

Appendix H Observation

The focus of the observation is based on the results of the pre-interview (quadrants 2 and 3).



Appendix I Participatory design activity 1 (process design)

Activity 1: Process Design

Purpose: to co-develop the design of your X assembly process

Motivation: to directly address perspectives on the assembly process that were shared in the interviews (codes 14, 15, 19, 11, 16, 17, 18, 23, 21, 22, 20, and 11 as shown in the interview results diagram and observation sheet). These perspectives include designing a process that "applies to us," "working smarter and not harder," "streamlining the process," "improving the flow," and reducing/eliminating the sorting process that occurs when the material counts are off.

Goals: to develop, analyze, and re-develop ideas for your X assembly process design relating to:

- Actions
- Methods
- Tools
- Tasks
- Sequencing of tasks
- Grouping of tasks and breakdown of tasks

Materials

- Boxes
- Old assembly components
- Different coloured electrical tape
- Scissors
- Work table
- Foam board
- Construction paper
- Other materials as requested by participants
- Sticky notes
- Chart paper
- Markers
- Timer
- Packing tape and dispenser
- Wheels
- Twine
- Different coloured blocks

Location: mock-area of the assembly area in the X. The boundaries of our mock-area are labeled with comparisons to the actual build area (e.g. wall, receiving area, forklift path, etc.).

Overview
We will go through a few cycles of design, and in each cycle you can experiment and make changes. We'll begin by looking at selecting the components for the assembly and we will add other aspects of the assembly process as we go. As you're designing, keep yourself and your fellow workers in mind -- what's important to you and your fellow workers? What would make this process best for you and your fellow workers?

Steps

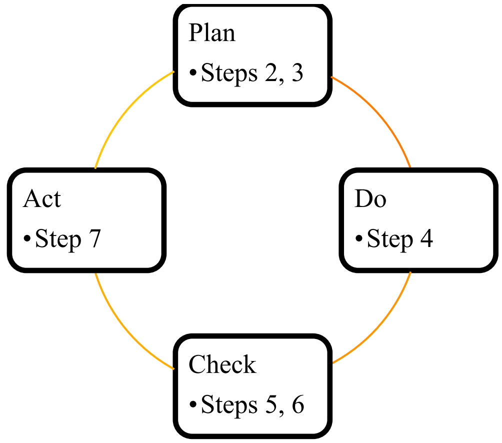
1. As a group, create a few orders for the assemblies. Decide how many finished assemblies you want to make and what assembly components (different parts and different quantities) that you want to include using the available materials. We'll call this the work order.
2. 2a. In your building process, how do you want to **select the components** each time that you build an assembly? One at a time? In groups? Using boxes? Etc. What would make choosing the components the easiest for you and your fellow workers?
3. Using any of the available materials, create anything that will help you to achieve your goals in step 2 (e.g. you could put something on wheels, you could have it at a certain height, etc.). Are there any tools that you could use or create to help you?
4. As a group, organize yourselves to fill your work orders (step 1) using your design(s). You decide who does what and when.
5. As you use your design(s), did your design work the way that you want it to? What worked? What didn't work? Would your design work for all different kinds of orders (quantity and for different types)?
6. Based on your experience with your design(s), what would you change?
7. Create the changes that you would like to make and repeat steps 3-7. After your design is working the way that you want it to, we'll look at the below variations of step 2 (2b-2d) and go through the cycle again.

2b. In your building process, how do you want to **put the components of the assembly together** (assemble them)? What would make putting the components together the easiest for you and your fellow workers?

2c. In your build process, how will you ensure that you **have selected the right components** for the order and have put them together according to the work order (ensuring quality)? What would make ensuring quality the easiest for you and your fellow workers?

2d. At the end of your build process, how will you **package the assembly** into the box and put it on a pallet? What would make packaging the assembly the easiest for your and your fellow workers?

Steps 2 – 7 of our design process are pictured below:



Other questions and notes:

- As you go through the cycle with 2b- 2d, does this affect the decisions that you made before?
- After you've completed the cycles and are happy with your design, how does this process design differ from the one that you work with now?
- At times, I (Victoria) may ask questions to better understand your design. For example, I may ask "what if…" questions. If you have any questions, please ask! I look forward to our discussions as we go along, and I'll be making some notes on the empathy board (chart paper) and on the observation sheets. I'm excited to see your designs!

Appendix J Participatory design activity 2 (layout/space design)

Activity 2: Layout/Space Design

Purpose: to co-develop the design of your X assembly process layout and space.

Motivation: to directly address perspectives on the assembly process that were shared in the interviews (codes 12, 13, 26 as shown in the interview results diagram and observation sheet). These perspectives include designing a layout that addresses "a sufficient amount of room," "we don't have the room," "limited room and space", "there is no designated take-up area," "maneuver[ing] skids in that small area," "more space away from forklifts," and in general organizing materials and having a designated position for materials and components that supports better flow ("I believe the flow should be a little bit better" and "Even it out so that there's a flow to it").

Goals: to develop, analyze, and re-develop ideas for the X assembly process layout design relating to:

- Designating layout areas (e.g. we need an area for this (and this))
- Locating layout areas (e.g. we need an area here)
- Describing contents for layout areas (e.g. we need these things in this area)
- Dimensioning layout areas (e.g. we need an area this big for these things)
- Positioning layout areas (e.g. we need an area for this next to this)
- Orienting layout areas (e.g. we need this facing…)
- Analyzing flow (e.g. we need to bring things into/out of the area in this direction)

Materials

- Boxes
- Old assembly components
- Different coloured electrical tape
- Scissors
- Work table
- Foam board
- Construction paper
- Other materials as requested by participants
- Sticky notes
- Chart paper
- Markers
- Timer
- Packing tape and dispenser
- Wheels
- Twine
- Different coloured blocks

Location: mock-area of the assembly area in the X. The boundaries of our mock-area are labeled with comparisons to the actual build area (e.g. wall, receiving area, forklift path, etc.).

Overview

We will go through a few cycles of design, and in each cycle you can experiment and make changes. We'll begin by looking at a location for selecting the components for the assembly and we will add other aspects of the assembly process as we go. As you're designing, keep yourself and your fellow workers in mind -- what's important to you and your fellow workers? What would make this process best for you and your fellow workers?

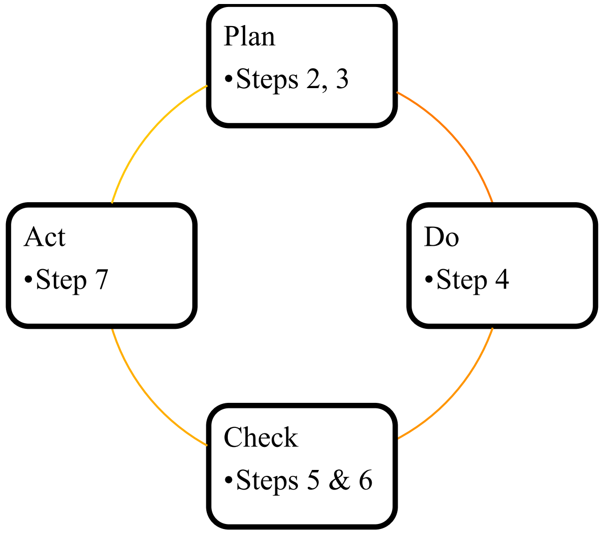
Steps

1. As a group, create a few orders for the assemblies. Decide how many finished assemblies you want to make and what assembly components (different parts and different quantities) that you want to include using the available materials. We'll call this the work order.
2. 2a. In your space, where do you want to **select the components** each time that you build an assembly? What would make getting the components the easiest for you and your fellow workers?
3. Using the different coloured electrical tape and any of the other materials, create your area to address step 2 using the following ideas:
    a. Red X marks the spot – the center of the area (location)
    b. Red lines mark the outer boundaries of the area (dimensions)
    c. Yellow lines mark anything inside the area that's important (contents). This might be a tool, machine, equipment, furniture, etc.
    d. Green arrow shows the direction that objects will move **<u>into</u>** the area (orientation, flow)
    e. Blue arrow shows the direction that objects will move **<u>out of</u>** the area (orientation, flow)
    f. Create any other rules that are helpful for your design and use any of the materials to build your design
4. As a group, organize yourselves to move the materials to complete your work orders (step 1) using your design(s). You decide who does what and when.
5. As you use your design(s), did your design work the way that you want it to? What worked? What didn't work? Would your design work for all different kinds of orders (quantity and for different types)?
6. Based on your experience with your design(s), what would you change?
7. Create the changes that you would like to make and repeat steps 2-8. After your design is working the way that you want it to, we'll look at the below variations of step 2 and go through the cycle again.

2b. In your space, where do you want to **assemble the components** each time that you build an assembly? What would make receiving the components the easiest for you and your fellow workers? With the red tape, mark an X on the floor in the center of where this area should be located.

2c. In your space, where do you want to **package the assemblies** each time that you build an assembly? What would make receiving the components the easiest for you and your fellow workers? With the red tape, mark an X on the floor in the center of where this area should be located.

Steps 2 – 7 of our design process are pictured below:



Other questions and notes:

- Are there any other areas that you would like to designate space for?
- As you go through the cycle with 2a- 2c, does this affect the decisions that you made before?
- Are there any changes that would impact your layout and space design? Can the design be changed to adapt to these changes?
- In the finished design, all your areas should be connected with arrows. On each arrow, mark whether you think that a person, a forklift, a pallet truck, and/or something else should move the materials along each arrow.
- After you've completed the cycles and are happy with your layout design, how does this layout differ from the one that you work with now?
- At times, I (Victoria) may ask questions to better understand your design. For example, I may ask "what if…" questions. If you have any questions, please ask! I look forward to our discussions as we go along, and I'll be making some notes on the empathy board (chart paper) and on the observation sheets. I'm excited to see your designs!

Appendix K Participatory design activity 3 (training design)

Activity 3: Training Design

Purpose: to co-develop the design of the training for your X assembly process and layout

Motivation: to directly address perspectives on the assembly process that were shared in the interviews (codes 9, 10, 24 as shown in the interview results diagram and observation sheet). These perspectives include designing training for people involved in the X assembly process (e.g. “training time,” “more training on setting up and staging,” and help for teaching people who are new to the process about the process).

Goals: to develop, analyze, and re-develop ideas for training on the X assembly process and layout design relating to:

- What needs to be known about the process and layout in different roles (knowledge, skills, and values)
- Relationships between what needs to be known (e.g. precedence/scaffolding)
- Effective means of learning

Materials

- Boxes
- Old assembly components
- Different coloured electrical tape
- Scissors
- Work table
- Foam board
- Construction paper
- Other materials as requested by participants
- Sticky notes
- Chart paper
- Markers
- Timer
- Packing tape and dispenser
- Wheels
- Twine
- Different coloured blocks

Location: mock-area of the assembly area in the X. The boundaries of our mock-area are labeled with comparisons to the actual build area (e.g. wall, receiving area, forklift path, etc.).

Overview
We will go through a few cycles of design, and in each cycle you can experiment and make changes. We’ll begin by looking at knowledge and skills related to selecting components for the assembly and we will add other aspects of the assembly process as we go. As you’re designing, keep yourself and your fellow workers in mind -- what’s important to you and your fellow workers? What would make this process best for you and your fellow workers?

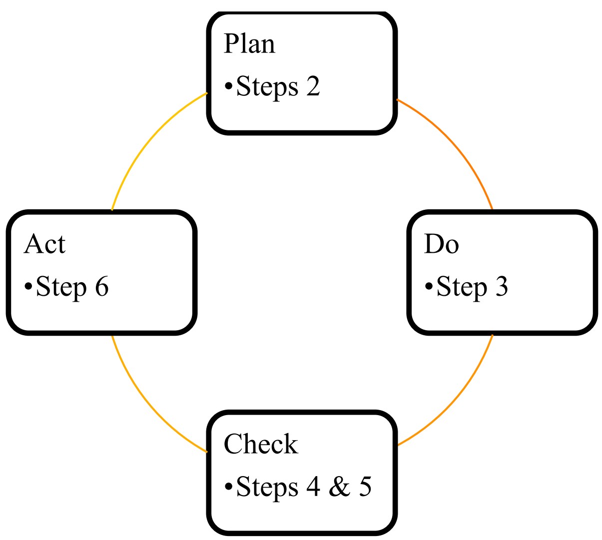
Steps

1. As a group, create a few orders for the assemblies. Decide how many finished assemblies you want to make and what assembly components (different parts and

different quantities) that you want to include using the available materials. We'll call this the work order.

2. In the areas that you've designated in your layout and process (e.g. area/stage for selecting components, assembly, packaging, etc.), what different things need to be known in that area (in that stage)? This could be knowledge about something (a concept), how to do something (a skill), or a value or belief in something (e.g. trust, respect, safety, etc.). Write each of your ideas on a sticky note and place it in that area. Keep in mind, what does a person need to know in order to do this job well? What knowledge would make performing this job the easiest for you and your fellow workers?
3. As a group, organize yourselves to move the materials through the layout and perform the process to fill the work order (step 1) using your designs. You decide who does what and when.
4. As you use your layout and process designs, did you include all of the necessary knowledge to work with the process and layout the way that you want to? What knowledge was important? Mark this with a star. What knowledge was missing? Create new sticky notes with this knowledge and add them where you think they should be.
5. Based on your experience with your designs, are there any changes that you'd like to make? To the design? To the knowledge that you've written down on the sticky notes?
6. Create the changes that you would like to make and repeat steps 2-6.

Steps 2 – 6 of our design process are pictured below:



Using all of the sticky notes that you've created, organize them according to the following ideas

- Each piece of chart paper represents a different role in the assembly process (e.g. builder). Label as many pieces of chart paper for the roles that you think should be represented.
- Each piece of knowledge (sticky note) should be assigned to a role (chart paper).

- If the same piece of knowledge (sticky note) should be assigned to more than one role (chart paper) then several sticky notes can be made
- Lines between sticky notes can indicate relationships (e.g. one piece of knowledge related to another)
- Arrows on a line can indicate directions of relationships (e.g. an arrow from A to B means that you need to know A before you can know B)
- Drawing a circle or box around several sticky notes can represent a group of things that belong together
- Use any other symbols or ways of organizing or analyzing the sticky notes that you want.

Keep in mind, what does a person need to know in order to do this job well? What knowledge would make performing this job the easiest for you and your fellow workers?

Once all of the sticky notes are organized on the chart paper in the way that you think is best, label each sticky note or groups of sticky notes with how you think that knowledge can be learned best. For example, do you think that learning it with a demonstration would be best? With a video, a visual diagram, written instructions? Are there other ways? Is more than one way important?

After you've completed your charts and are happy with your training design, how does this training differ from the training that you have now?

At times, I (Victoria) may ask questions to better understand your design. For example, I may ask "what if…" questions. If you have any questions, please ask! I look forward to our discussions as we go along, and I'll be making some notes on the empathy board (chart paper) and on the observation sheets. I'm excited to see your designs!

Appendix L Participatory design activity 3 (training design) revised

Participatory Design Activity #3 – Training Design

Purpose: to co-develop the design of the training for your X assembly process and layout

Motivation: to directly address perspectives on the assembly process that were shared in the interviews (codes 9, 10, 24 as shown in the interview results diagram and observation sheet). These perspectives include designing training for people involved in the X assembly process (e.g. "training time," "more training on setting up and staging," and help for teaching people who are new to the process about the process).

Goals: to develop, analyze, and re-develop ideas for training on the X assembly process and layout design relating to:

- What needs to be known about the process and layout in different roles (knowledge, skills, and values)
- Relationships between what needs to be known (e.g. precedence/scaffolding)
- Effective means of learning

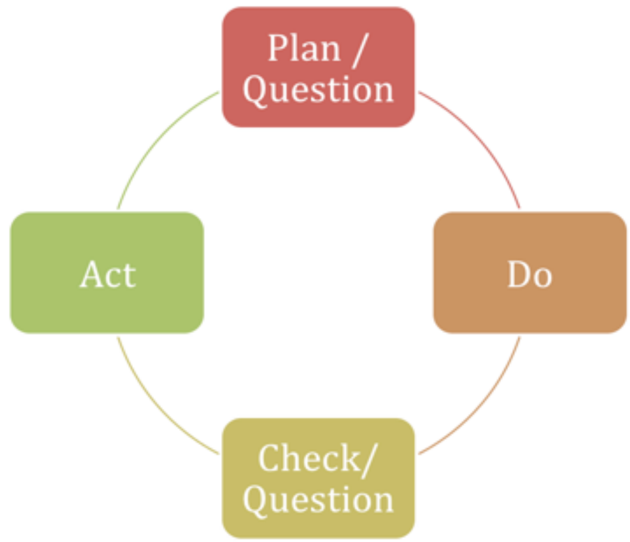
Materials

- Boxes
- Old assembly components
- Different coloured electrical tape
- Scissors
- Work table
- Foam board
- Construction paper
- Other materials as requested by participants
- Sticky notes
- Chart paper
- Markers
- Timer
- Packing tape and dispenser
- Wheels
- Twine
- Different coloured blocks

Location: assembly area in the X and meeting room.

Overview

We will go through a few cycles of design, and in each cycle you can experiment and make changes. As you're designing, keep yourself and your fellow workers in mind -- what's important to you and your fellow workers? What would make this process best for you and your fellow workers?



Steps
See/experience the process and layout as designed by participants in participatory design

- Few trials of building
- Opportunity to observe, talk, and think aloud while doing

Based on this experience, what is important to consider in the training design? Are there any questions that you think we should answer together while we design the training?

- Written individually
- Shared as a group, facilitator writing them down on chart paper or white board

What are the process steps in the process and what are different people doing at each of the steps in the process?

- 2 groups
- Free process mapping (similar to free writing), utilizing available materials

What do different people need to know at each of these steps?

- 2 groups, change

What's similar or different between the two group designs? Can we combine them?

- Discuss as a group

What form should this training take?

- Based on what people need to know at different steps in the process, how could the different stakeholders learn this best?
- Brainstorm list (flip chart and create cards) as group
- Card sorting to inquire into priorities (pairs)
- Discuss results as group – select approx. 2 to start with

Based on your findings, what forms of training do we want to begin to design?

- Groups utilize available materials to build prototypes

Reflecting back on initial considerations and questions on training design – did we address these considerations and questions?

- Discuss as a group

What are the next steps?

- Discuss as a group

How would you describe your experience with participatory design?

- Anonymous and voluntary, written on paper and submitted into an envelope

At times, I (Victoria) may ask questions to better understand your design. For example, I may ask "what if…" questions. If you have any questions, please ask! I look forward to our discussions as we go along, and I'll be making some notes on the empathy board (chart paper) and on the observation sheets. I'm excited to see your designs!

Appendix M Post-survey

Post-survey test instrument

Post-Survey
This survey is for participants in the process research study. If you are unable to answer a question, you can select N/A (not applicable) or leave it blank and go to the next question.
Thank you for your participation.

1. Which phases of the research study have you participated in? Select ***all*** of the circles that apply.

○	○	○	○	⊗
Pre-interview (Sept. 2013)	Pre-Observation (Nov. 2013 – Jan. 2014)	Participatory Design Events (May – June 2014)	Post-Observation (Sept. – Oct. 2014)	Post-survey

2. To what extent do you agree or disagree with each of the following statements when comparing the new process design to the old design? Select ***one*** circle for each statement. The new design refers to the process, layout, and training designs that you participated in creating and working with.

The new design has improved builder responsibility and independence.

○	○	○	○	○
Strongly Disagree	Disagree	Neutral or N/A	Agree	Strongly Agree

The new design has improved quality by better ensuring that the correct number of each material is used.

○	○	○	○	○
Strongly Disagree	Disagree	Neutral or N/A	Agree	Strongly Agree

The new design has improved the utilization of limited room and space.

○	○	○	○	○
Strongly Disagree	Disagree	Neutral or N/A	Agree	Strongly Agree

The new design has improved the organization of the materials and components.

○	○	○	○	○
Strongly Disagree	Disagree	Neutral or N/A	Agree	Strongly Agree

The new design has improved the order of tasks involved in making.

○	○	○	○	○
Strongly Disagree	Disagree	Neutral or N/A	Agree	Strongly Agree

The new design has improved the division of work between the builders (i.e. deciding who does what).

○	○	○	○	○
Strongly Disagree	Disagree	Neutral or N/A	Agree	Strongly Agree

The new design has improved the ability for new builders to learn the process and work.

○	○	○	○	○
Strongly Disagree	Disagree	Neutral or N/A	Agree	Strongly Agree

The new design has improved the flow of materials, components, and final

○	○	○	○	○
Strongly Disagree	Disagree	Neutral or N/A	Agree	Strongly Agree

The new design has improved the flow of people involved in work.

Strongly Disagree — Disagree — Neutral or N/A — Agree — Strongly Agree

The new design has improved the ability for us to work smarter not harder when building

Strongly Disagree — Disagree — Neutral or N/A — Agree — Strongly Agree

The new design has improved the communication between different people involved in building

Strongly Disagree — Disagree — Neutral or N/A — Agree — Strongly Agree

The new design applies to us.

Strongly Disagree — Disagree — Neutral or N/A — Agree — Strongly Agree

The new design is fair (or just).

Strongly Disagree — Disagree — Neutral or N/A — Agree — Strongly Agree

Are there any other improvements with new design(s) that you can think of? Please explain.

____
____
____
____
____

3. The following design ideas for the process, layout, and training arose out of the design events. Please place a “1” and “2” beside the two design ideas that you think are the ***most*** important. Please place an “X” beside the two design ideas that you think are the ***least*** important.

	Changing the location of the build table (rotating it 90 degrees)
	New layout diagram (designating locations for pallets, etc.)
	Moving the paper machine and learning how to use it to its full potential
	Grid on the table with locations for the different materials
	Labeling system for the grid on the table and pallets (colour-coded, laminated tags with Velcro)
	Two roles for the builders – one picker, one assembler
	Checklist for the different builder tasks (for the picker, assembler, and some shared)
	Demonstration of the process with the new builders (setting up the example with them)
	Specific people designated as a “ trainer”
	Sample of the paperwork with different areas highlighted to explain it
	Making a priority for the lead hand, secondary to receiving
	Communication board (including average times, language (e.g. UPC, shippers, CHEP), etc.)
	Walkie-talkies for the builders to communicate with others (e.g. lead hands, material handlers)
	All cases to come in a coffin-like shipper
	training checklist (including showing how to block and brace, shake test, etc.)

Are there any other design ideas that you think are important?

4. Based on your experience with the new and old assembly designs (process, layout, and training), what do you think makes a good design? You can answer this specifically (for process, layout, and/or training) or in general (considering all of them together) or both.

5. Based on your experience with the design process in this study, how would you connect the following concepts of the design process with arrows? You can draw as many arrows as you like, create new words in any space, use all of the words or only some, group the words (e.g. with a circle), etc.

Opportunity

Detail
(Specific idea)

Concept
(Broad idea)

Problem

Need

Question

6. Based on your experience with the design process in this study, what do you think makes a good design process?

7. Are there other situations in manufacturing that you think a participatory design approach, like the one you experienced, could be used?

8. Are there other situations in manufacturing that you think a participatory design approach, like the one you experienced, could ***not*** be used?

9. Through your participation in this research study, how would you rate the following?

I believe that my voice was heard in the design process.

Strongly Disagree	Disagree	Neutral or N/A	Agree	Strongly Agree

I had a say (or influence) in the design process.

Strongly Disagree	Disagree	Neutral or N/A	Agree	Strongly Agree

I participated in decision-making in the design process.

Strongly Disagree	Disagree	Neutral or N/A	Agree	Strongly Agree

I participated in creating positive change in my work environment.

Strongly Disagree	Disagree	Neutral or N/A	Agree	Strongly Agree

I learned new things from my participation in the design process.

Strongly Disagree	Disagree	Neutral or N/A	Agree	Strongly Agree

10. Through your participation in this research study, is there anything that you especially liked participating in?

____
____
____
____
____

11. Through your participation in this research study, is there anything that you did ***not*** like experiencing or participating in?

____
____
____
____
____

12. Do you have any other comments that you'd like to add?

____
____
____
____
____

We ***may*** conduct a few post-interviews following this survey based on the responses and roles related to the assembly process. Would you be interested in being contacted for a post-interview? If so, please list your name below and times that you are available for a post-interview.

____
Name – if you are interested in a potential post-interview

____
Dates and times – that you are available for a post-interview

If you prefer, you can also contact me directly at to indicate your interest in a post-interview.

Thank you for participating in this survey and in this research study.
Sincerely, Victoria

Appendix N Copyright forms

COPYRIGHT AGREEMENT (as of February 2010)

ASME Publishing • Two Park Avenue • New York, NY 10016
For questions about Conference paper copyright, please e-mail copyright@asme.org
For questions about Journal paper copyright, please email journalcopyright@asme.org

Before publication of your paper in a conference proceedings or journal, ASME must receive a signed Copyright Agreement. For conference papers, this form should be received by the deadline indicated by the Conference. Other forms may NOT be substituted for this form, nor may any wording on the form be changed.

PAPER NUMBER (for conference/journal papers): IMECE2014-38492

TITLE: An Ethical Roadmap for Engineering Participatory Design and Sociotechnical Participation: A Manufacturing Case Study

AUTHOR(s): Victoria Townsend, Pierre Boulos, Ruth Jill Urbanic

CONFERENCE NAME: IMECE

JOURNAL NAME: ______

ASME requests that authors/copyright owners assign copyright to ASME in order for a conference or journal paper to be published by ASME. Authors exempt from this request are direct employees of the U.S. Government, whereby papers are not subject to copyright protection in the U.S., or non-U.S. government employees, whose governments hold the copyright to the paper. Otherwise, the author/ copyright owner(s) of the Paper should sign this form as instructed below. Please refer to the section below "Who Should Sign" and also to ASME's FAQ page for more information regarding copyright ownership and the copyright process.

WHO SHOULD SIGN

Only the copyright owner(s) of the Paper, or an authorized representative, can sign this form. If one of the following applies, you may not own the copyright to the paper, or you may not be authorized to sign this agreement, and you may need to have the appropriate copyright owner(s) or organization representative sign this Agreement:
(1) You created the Paper within the scope of your employment, and your employer is the copyright owner
(2) You created the Paper under an independent contractor agreement**
(3) You received a grant that funded your Paper.

Please review your company policies regarding copyright, and if you are not authorized to sign this agreement, please forward to the appropriate organization representative. Please review applicable company, institutional, and grant policies and your employment/independent contractor agreement to determine who holds the rights to your Paper. For more information, please refer to the FAQs.

****Note to U.S. Government Contractors:** If you created the Paper under contract with the U.S. Government, e.g., U.S. Government labs, the paper may be subject to copyright, and you or your employer may own the copyright. Please review your company/institutional policies and your contractor agreement. Your Paper may also require a footer acknowledging contract information and also the following statement:

"The United States Government retains, and by accepting the article for publication, the publisher acknowledges that the United States Government retains, a non-exclusive, paid-up, irrevocable, worldwide license to publish or reproduce the published form of this work, or allow others to do so, for United States Government purposes."

It is your responsibility to ensure that the final PDF version of the Paper you submit includes all necessary footers and statements required under your contract.

COPYRIGHT ASSIGNMENT

The following terms of copyright assignment refer to Sections 1, 2, and 3. Sections 4 and 5 may not be subject to copyright.

The undersigned hereby assigns irrevocably to ASME all worldwide rights under copyright in the Paper.

Authors retain all proprietary rights in any idea, process, procedure, or articles of manufacture described in the Paper, including the right to seek patent protection for them. Authors may perform, lecture, teach, conduct related research, display all or part of the Paper, and create derivative works in print or electronic format. Authors may reproduce and distribute the Paper for non-commercial purposes only. Non-commercial applies only to the sale of the paper per se. For all copies of the Paper made by Authors, Authors must acknowledge ASME as original publisher and include the names of all author(s), the publication title, and an appropriate copyright notice that identifies ASME as the copyright holder.

PLEASE READ THE TERMS AND CONDITIONS WHICH ARE FULLY INCORPORATED IN THIS AGREEMENT.

PAPERS OWNED BY ONE AUTHOR OR JOINT AUTHORS; DESIGNATED AUTHORS (For jointly authored works, all authors should submit a signed Agreement, or one Designated Author may sign on behalf of the other authors, but ONLY IF the designated author has secured written authorization to do so from all other authors. The designated author must be able to produce such written authorization if requested.)

Author, Co-Author, or Designated Author

Name: Victoria Townsend Signature: Victoria Townsend Date: 02 Jun 2014

Affiliation: University of Windsor, Dept. of Industrial and Manufacturing Systems Engineering (Company or Institution) Title: PhD Candidate

Street Address: 401 Sunset Ave.

Windsor (City) ON (State) N9B 3P4 (Zip Code) Canada (Country)

Phone: ____ Fax: ____ Email: ____

Author: (Applied only if you are signing for other)

Name: ____ Signature: ____ Date: ____

Affiliation: ____ (Company or Institution) Title: ____

Street Address: ____

____ (City) (State) (Zip Code) (Country)

Phone: ____ Fax: ____ Email: ____

Copyright Clearance Center RightsLink®

Home | Account Info | Help | Live Chat

Title:	Complexity Analysis for Problem Definition in an Assemble-to-order Process: Engaging Emic and Etic Perspectives
Author:	Victoria Townsend,Jill Urbanic
Publication:	Procedia CIRP
Publisher:	Elsevier
Date:	2014

Logged in as:
Victoria Townsend
LOGOUT

ELSEVIER

Order Completed

Thank you very much for your order.

This is a License Agreement between Victoria Townsend ("You") and Elsevier ("Elsevier"). The license consists of your order details, the terms and conditions provided by Elsevier, and the payment terms and conditions.

Get the printable license.

License Number	3742621147442
License date	Nov 05, 2015
Licensed content publisher	Elsevier
Licensed content publication	Procedia CIRP
Licensed content title	Complexity Analysis for Problem Definition in an Assemble-to-order Process: Engaging Emic and Etic Perspectives
Licensed content author	Victoria Townsend,Jill Urbanic
Licensed content date	2014
Licensed content volume number	17
Licensed content issue number	n/a
Number of pages	6
Type of Use	reuse in a thesis/dissertation
Portion	excerpt
Number of excerpts	4
Format	both print and electronic
Are you the author of this Elsevier article?	Yes
Will you be translating?	No
Title of your thesis/dissertation	From Participation to Differentiation: A Framework for Re-Designing a Socio-Technical System
Expected completion date	Dec 2015
Estimated size (number of pages)	350
Elsevier VAT number	GB 494 6272 12
Permissions price	0.00 USD
VAT/Local Sales Tax	0.00 USD / 0.00 GBP
Total	0.00 USD

ORDER MORE... | CLOSE WINDOW

Where “An excerpt is less than 500 words of content, not including figures, tables, and illustrations on the page(s), if any. You may reuse multiple excerpts. Please enter the quantity you wish to license below.”

ELSEVIER LICENSE
TERMS AND CONDITIONS

Nov 05, 2015

This is a License Agreement between Victoria Townsend ("You") and Elsevier ("Elsevier") provided by Copyright Clearance Center ("CCC"). The license consists of your order details, the terms and conditions provided by Elsevier, and the payment terms and conditions.

All payments must be made in full to CCC. For payment instructions, please see information listed at the bottom of this form.

Supplier	Elsevier Limited The Boulevard,Langford Lane Kidlington,Oxford,OX5 1GB,UK
Registered Company Number	1982084
Customer name	Victoria Townsend
Customer address	
License number	3742621147442
License date	Nov 05, 2015
Licensed content publisher	Elsevier
Licensed content publication	Procedia CIRP
Licensed content title	Complexity Analysis for Problem Definition in an Assemble-to-order Process: Engaging Emic and Etic Perspectives
Licensed content author	Victoria Townsend,Jill Urbanic
Licensed content date	2014
Licensed content volume number	17
Licensed content issue number	n/a
Number of pages	6
Start Page	201
End Page	206
Type of Use	reuse in a thesis/dissertation
Portion	excerpt
Number of excerpts	4
Format	both print and electronic
Are you the author of this Elsevier article?	Yes
Will you be translating?	No
Title of your thesis/dissertation	From Participation to Differentiation: A Framework for Re-Designing a Socio-Technical System

Expected completion date	Dec 2015
Estimated size (number of pages)	350
Elsevier VAT number	GB 494 6272 12
Permissions price	0.00 USD
VAT/Local Sales Tax	0.00 USD / 0.00 GBP
Total	0.00 USD
Terms and Conditions	

INTRODUCTION

1. The publisher for this copyrighted material is Elsevier. By clicking "accept" in connection with completing this licensing transaction, you agree that the following terms and conditions apply to this transaction (along with the Billing and Payment terms and conditions established by Copyright Clearance Center, Inc. ("CCC"), at the time that you opened your Rightslink account and that are available at any time at http://myaccount.copyright.com).

GENERAL TERMS

2. Elsevier hereby grants you permission to reproduce the aforementioned material subject to the terms and conditions indicated.

3. Acknowledgement: If any part of the material to be used (for example, figures) has appeared in our publication with credit or acknowledgement to another source, permission must also be sought from that source. If such permission is not obtained then that material may not be included in your publication/copies. Suitable acknowledgement to the source must be made, either as a footnote or in a reference list at the end of your publication, as follows:

"Reprinted from Publication title, Vol /edition number, Author(s), Title of article / title of chapter, Pages No., Copyright (Year), with permission from Elsevier [OR APPLICABLE SOCIETY COPYRIGHT OWNER]." Also Lancet special credit - "Reprinted from The Lancet, Vol. number, Author(s), Title of article, Pages No., Copyright (Year), with permission from Elsevier."

4. Reproduction of this material is confined to the purpose and/or media for which permission is hereby given.

5. Altering/Modifying Material: Not Permitted. However figures and illustrations may be altered/adapted minimally to serve your work. Any other abbreviations, additions, deletions and/or any other alterations shall be made only with prior written authorization of Elsevier Ltd. (Please contact Elsevier at permissions@elsevier.com)

6. If the permission fee for the requested use of our material is waived in this instance, please be advised that your future requests for Elsevier materials may attract a fee.

7. Reservation of Rights: Publisher reserves all rights not specifically granted in the combination of (i) the license details provided by you and accepted in the course of this licensing transaction, (ii) these terms and conditions and (iii) CCC's Billing and Payment terms and conditions.

8. License Contingent Upon Payment: While you may exercise the rights licensed immediately upon issuance of the license at the end of the licensing process for the transaction, provided that you have disclosed complete and accurate details of your proposed use, no license is finally effective unless and until full payment is received from you (either by publisher or by CCC) as provided in CCC's Billing and Payment terms and conditions. If full payment is not received on a timely basis, then any license preliminarily granted shall be deemed automatically revoked and shall be void as if never granted. Further, in the event

that you breach any of these terms and conditions or any of CCC's Billing and Payment terms and conditions, the license is automatically revoked and shall be void as if never granted. Use of materials as described in a revoked license, as well as any use of the materials beyond the scope of an unrevoked license, may constitute copyright infringement and publisher reserves the right to take any and all action to protect its copyright in the materials.

9. Warranties: Publisher makes no representations or warranties with respect to the licensed material.

10. Indemnity: You hereby indemnify and agree to hold harmless publisher and CCC, and their respective officers, directors, employees and agents, from and against any and all claims arising out of your use of the licensed material other than as specifically authorized pursuant to this license.

11. No Transfer of License: This license is personal to you and may not be sublicensed, assigned, or transferred by you to any other person without publisher's written permission.

12. No Amendment Except in Writing: This license may not be amended except in a writing signed by both parties (or, in the case of publisher, by CCC on publisher's behalf).

13. Objection to Contrary Terms: Publisher hereby objects to any terms contained in any purchase order, acknowledgment, check endorsement or other writing prepared by you, which terms are inconsistent with these terms and conditions or CCC's Billing and Payment terms and conditions. These terms and conditions, together with CCC's Billing and Payment terms and conditions (which are incorporated herein), comprise the entire agreement between you and publisher (and CCC) concerning this licensing transaction. In the event of any conflict between your obligations established by these terms and conditions and those established by CCC's Billing and Payment terms and conditions, these terms and conditions shall control.

14. Revocation: Elsevier or Copyright Clearance Center may deny the permissions described in this License at their sole discretion, for any reason or no reason, with a full refund payable to you. Notice of such denial will be made using the contact information provided by you. Failure to receive such notice will not alter or invalidate the denial. In no event will Elsevier or Copyright Clearance Center be responsible or liable for any costs, expenses or damage incurred by you as a result of a denial of your permission request, other than a refund of the amount(s) paid by you to Elsevier and/or Copyright Clearance Center for denied permissions.

LIMITED LICENSE

The following terms and conditions apply only to specific license types:

15. **Translation**: This permission is granted for non-exclusive world **English** rights only unless your license was granted for translation rights. If you licensed translation rights you may only translate this content into the languages you requested. A professional translator must perform all translations and reproduce the content word for word preserving the integrity of the article.

16. **Posting licensed content on any Website**: The following terms and conditions apply as follows: Licensing material from an Elsevier journal: All content posted to the web site must maintain the copyright information line on the bottom of each image; A hyper-text must be included to the Homepage of the journal from which you are licensing at http://www.sciencedirect.com/science/journal/xxxxx or the Elsevier homepage for books at http://www.elsevier.com; Central Storage: This license does not include permission for a scanned version of the material to be stored in a central repository such as that provided by Heron/XanEdu.

Licensing material from an Elsevier book: A hyper-text link must be included to the Elsevier homepage at http://www.elsevier.com . All content posted to the web site must maintain the copyright information line on the bottom of each image.

Posting licensed content on Electronic reserve: In addition to the above the following clauses are applicable: The web site must be password-protected and made available only to bona fide students registered on a relevant course. This permission is granted for 1 year only. You may obtain a new license for future website posting.
17. **For journal authors:** the following clauses are applicable in addition to the above:
Preprints:
A preprint is an author's own write-up of research results and analysis, it has not been peer-reviewed, nor has it had any other value added to it by a publisher (such as formatting, copyright, technical enhancement etc.).
Authors can share their preprints anywhere at any time. Preprints should not be added to or enhanced in any way in order to appear more like, or to substitute for, the final versions of articles however authors can update their preprints on arXiv or RePEc with their Accepted Author Manuscript (see below).
If accepted for publication, we encourage authors to link from the preprint to their formal publication via its DOI. Millions of researchers have access to the formal publications on ScienceDirect, and so links will help users to find, access, cite and use the best available version. Please note that Cell Press, The Lancet and some society-owned have different preprint policies. Information on these policies is available on the journal homepage.
Accepted Author Manuscripts: An accepted author manuscript is the manuscript of an article that has been accepted for publication and which typically includes author-incorporated changes suggested during submission, peer review and editor-author communications.
Authors can share their accepted author manuscript:

- immediately
    - via their non-commercial person homepage or blog
    - by updating a preprint in arXiv or RePEc with the accepted manuscript
    - via their research institute or institutional repository for internal institutional uses or as part of an invitation-only research collaboration work-group
    - directly by providing copies to their students or to research collaborators for their personal use
    - for private scholarly sharing as part of an invitation-only work group on commercial sites with which Elsevier has an agreement
- after the embargo period
    - via non-commercial hosting platforms such as their institutional repository
    - via commercial sites with which Elsevier has an agreement

In all cases accepted manuscripts should:

- link to the formal publication via its DOI
- bear a CC-BY-NC-ND license - this is easy to do
- if aggregated with other manuscripts, for example in a repository or other site, be shared in alignment with our hosting policy not be added to or enhanced in any way to appear more like, or to substitute for, the published journal article.

Published journal article (JPA): A published journal article (PJA) is the definitive final record of published research that appears or will appear in the journal and embodies all value-adding publishing activities including peer review co-ordination, copy-editing,

formatting, (if relevant) pagination and online enrichment.
Policies for sharing publishing journal articles differ for subscription and gold open access articles:
Subscription Articles: If you are an author, please share a link to your article rather than the full-text. Millions of researchers have access to the formal publications on ScienceDirect, and so links will help your users to find, access, cite, and use the best available version.
Theses and dissertations which contain embedded PJAs as part of the formal submission can be posted publicly by the awarding institution with DOI links back to the formal publications on ScienceDirect.
If you are affiliated with a library that subscribes to ScienceDirect you have additional private sharing rights for others' research accessed under that agreement. This includes use for classroom teaching and internal training at the institution (including use in course packs and courseware programs), and inclusion of the article for grant funding purposes.
Gold Open Access Articles: May be shared according to the author-selected end-user license and should contain a CrossMark logo, the end user license, and a DOI link to the formal publication on ScienceDirect.
Please refer to Elsevier's posting policy for further information.
18. **For book authors** the following clauses are applicable in addition to the above:
Authors are permitted to place a brief summary of their work online only. You are not allowed to download and post the published electronic version of your chapter, nor may you scan the printed edition to create an electronic version. **Posting to a repository:** Authors are permitted to post a summary of their chapter only in their institution's repository.
19. **Thesis/Dissertation**: If your license is for use in a thesis/dissertation your thesis may be submitted to your institution in either print or electronic form. Should your thesis be published commercially, please reapply for permission. These requirements include permission for the Library and Archives of Canada to supply single copies, on demand, of the complete thesis and include permission for Proquest/UMI to supply single copies, on demand, of the complete thesis. Should your thesis be published commercially, please reapply for permission. Theses and dissertations which contain embedded PJAs as part of the formal submission can be posted publicly by the awarding institution with DOI links back to the formal publications on ScienceDirect.

Elsevier Open Access Terms and Conditions
You can publish open access with Elsevier in hundreds of open access journals or in nearly 2000 established subscription journals that support open access publishing. Permitted third party re-use of these open access articles is defined by the author's choice of Creative Commons user license. See our open access license policy for more information.
Terms & Conditions applicable to all Open Access articles published with Elsevier:
Any reuse of the article must not represent the author as endorsing the adaptation of the article nor should the article be modified in such a way as to damage the author's honour or reputation. If any changes have been made, such changes must be clearly indicated.
The author(s) must be appropriately credited and we ask that you include the end user license and a DOI link to the formal publication on ScienceDirect.
If any part of the material to be used (for example, figures) has appeared in our publication with credit or acknowledgement to another source it is the responsibility of the user to ensure their reuse complies with the terms and conditions determined by the rights holder.
Additional Terms & Conditions applicable to each Creative Commons user license:
CC BY: The CC-BY license allows users to copy, to create extracts, abstracts and new works from the Article, to alter and revise the Article and to make commercial use of the Article (including reuse and/or resale of the Article by commercial entities), provided the

Copyright Clearance Center RightsLink® Account Info Help Live Chat

Title:	Complexity Analysis for Problem Definition in an Assemble-to-order Process: Engaging Emic and Etic Perspectives
Author:	Victoria Townsend,Jill Urbanic
Publication:	Procedia CIRP
Publisher:	Elsevier
Date:	Jan 1, 2014

Logged in as:
Victoria Townsend
Account #:
3000972247
LOGOUT

Order Completed

Thank you for your order.

This Agreement between Victoria Townsend ("You") and Elsevier ("Elsevier") consists of your order details and the terms and conditions provided by Elsevier and Copyright Clearance Center.

License number	Reference confirmation email for license number
License date	Nov 05, 2015
Licensed content publisher	Elsevier
Licensed content publication	Procedia CIRP
Licensed content title	Complexity Analysis for Problem Definition in an Assemble-to-order Process: Engaging Emic and Etic Perspectives
Licensed content author	Victoria Townsend,Jill Urbanic
Licensed content date	2014
Licensed content volume number	17
Licensed content issue number	n/a
Number of pages	6
Type of Use	reuse in a thesis/dissertation
Portion	figures/tables/illustrations
Number of figures/tables/illustrations	>10
Actual number of figures/tables/illustrations	13
Format	both print and electronic
Are you the author of this Elsevier article?	Yes
Will you be translating?	No
Original figure numbers	Fig. 1, Fig. 2, Fig. 3, Fig. 4, Fig. 5, Fig. 6, Table 2, Table 3, Equation 1, Equation 2, Equation 3, Equation 4, Equation 5
Title of your thesis/dissertation	From Participation to Differentiation: A Framework for Re-Designing a Socio-Technical System
Expected completion date	Dec 2015
Elsevier VAT number	GB 494 6272 12
Billing Type	Invoice
Billing address	Victoria Townsend Attn: Victoria Townsend
Permissions price	0.00 USD

ELSEVIER LICENSE
TERMS AND CONDITIONS

Nov 09, 2015

This is a License Agreement between Victoria Townsend ("You") and Elsevier ("Elsevier") provided by Copyright Clearance Center ("CCC"). The license consists of your order details, the terms and conditions provided by Elsevier, and the payment terms and conditions.

All payments must be made in full to CCC. For payment instructions, please see information listed at the bottom of this form.

Supplier	Elsevier Limited The Boulevard,Langford Lane Kidlington,Oxford,OX5 1GB,UK
Registered Company Number	1982084
Customer name	Victoria Townsend
Customer address	
License number	3743110252441
License date	Nov 05, 2015
Licensed content publisher	Elsevier
Licensed content publication	Procedia CIRP
Licensed content title	Complexity Analysis for Problem Definition in an Assemble-to-order Process: Engaging Emic and Etic Perspectives
Licensed content author	Victoria Townsend,Jill Urbanic
Licensed content date	2014
Licensed content volume number	17
Licensed content issue number	n/a
Number of pages	6
Start Page	201
End Page	206
Type of Use	reuse in a thesis/dissertation
Intended publisher of new work	other
Portion	figures/tables/illustrations
Number of figures/tables/illustrations	>10
Actual number of figures/tables/illustrations	13
Format	both print and electronic

Are you the author of this Elsevier article?	Yes
Will you be translating?	No
Original figure numbers	Fig. 1, Fig. 2, Fig. 3, Fig. 4, Fig. 5, Fig. 6, Table 2, Table 3, Equation 1, Equation 2, Equation 3, Equation 4, Equation 5
Title of your thesis/dissertation	From Participation to Differentiation: A Framework for Re-Designing a Socio-Technical System
Expected completion date	Dec 2015
Estimated size (number of pages)	
Elsevier VAT number	GB 494 6272 12
Permissions price	0.00 USD
VAT/Local Sales Tax	0.00 USD / 0.00 GBP
Total	0.00 USD
Terms and Conditions	

Authors' Rights
Help | Print

JOURNAL PUBLISHING AND LICENSING AGREEMENT

Elsevier B.V.

Article:	**A Case Study Measuring the Impact of a Participatory Design Intervention on System Complexity and Cycle Time in an Assemble-to-Order System**
Corresponding author:	**Dr. Victoria Townsend**
E-mail address:	**townsenv@uwindsor.ca;jurbanic@uwindsor.ca**
Journal:	**Procedia Manufacturing**
Our reference	**PROMFG1290**
PII:	**S2351-9789(15)01076-8**
DOI:	**10.1016/j.promfg.2015.09.076**

YOUR STATUS

- I am one author signing on behalf of all co-authors of the manuscript
- I am signing on behalf of the corresponding author.
  Name/Job title/Company: R. Jill Urbanic, PEng, PhD, Associate Professor, University of Windsor
  E-mail addres

DATA PROTECTION & PRIVACY

- I do not wish to receive news, promotions and special offers about products and services from Elsevier B.V. and its affiliated comp

LICENSE OF PUBLISHING RIGHTS

I hereby grant to Elsevier B.V. (hereinafter the "Journal") an exclusive publishing and distribution license in the manuscript identified above and any tables, illustrations or other information submitted for publication as part of the manuscript (the "Article") in all forms and media (whether now known or hereafter developed), throughout the world, in all languages, for the full term of copyright, effective when the Article is accepted for publication. This license includes the right to enforce the rights granted by this license against third parties and to sublicense such rights.

SUPPLEMENTAL MATERIALS

With respect to Supplemental Materials that I wish to make accessible either through a link in the Article or on a site or through a service of Elsevier B.V., Elsevier B.V. shall be entitled to publish, post, reformat, index, archive, make available and link to such Supplemental Materials on a non-exclusive basis, in all forms and media (whether now known or later developed) and permit others to do so. "Supplemental Materials" shall mean additional materials that are not an intrinsic part of the Article, including but not limited to experimental data, e-components, encodings and software, and enhanced graphical, illustrative, video and audio material.

SCHOLARLY COMMUNICATION RIGHTS

I understand that I retain the copyright in the Article and that no rights in patents, trademarks or other intellectual property rights are transferred to the Journal. As the author of the Article, I understand that I shall have: (i) the same rights to reuse the Article as those allowed to third party users of the Article under the CC BY-NC-ND License, as well as (ii) the right to use the Article in a subsequent compilation of my works or to extend the Article to book length form, to include the Article in a thesis or dissertation, or otherwise to use or re-use portions or excerpts in other works, for both commercial and non-commercial purposes. Except for such uses, I understand that the license of publishing rights I have granted to the Journal gives the Journal the exclusive right to make or sub-license commercial use.

USER RIGHTS

The publisher will apply the *Creative Commons Attribution-Noncommercial-NoDerivative Works 4.0 International License* (CC BY-NC-ND) to the Article where it publishes the Article in the journal on its online platforms on an Open Access basis. For further information, see http://www.elsevier.com/about/open-access/open-access-options.

The CC BY-NC-ND license allows users to copy and distribute the Article, provided this is not done for commercial purposes and further does not permit distribution of the Article if it is changed or edited in any way, and provided the user gives appropriate credit (with a link to the formal publication through the relevant DOI), provides a link to the license, and that the licensor is not represented as endorsing the use made of the work. The full details of the license are available at http://creativecommons.org/licenses/by-nc-nd/4.0.

REVERSION OF RIGHTS

Articles may sometimes be accepted for publication but later rejected in the publication process, even in some cases after public posting in "Articles in Press" form, in which event all rights will revert to the author. See http://www.elsevier.com/locate/withdrawalpolicy.

REVISIONS AND ADDENDA

I understand that no revisions, additional terms or addenda to this License Agreement can be accepted without the Journal's express written consent. I understand that this License Agreement supersedes any previous agreements I have entered into with the Journal in relation to the Article from the date hereof.

COPYRIGHT NOTICE

The publisher shall publish and distribute the Article with the appropriate copyright notice.

AUTHOR REPRESENTATIONS / ETHICS AND DISCLOSURE

I affirm the Author Representations noted below, and confirm that I have reviewed and complied with the relevant Instructions to Authors, Ethics in Publishing policy, and Conflicts of Interest disclosure. Please note that some journals may require that all co-authors sign and submit Conflicts of Interest disclosure forms. I am also aware of the publisher's policies with respect to retractions and withdrawal (http://www.elsevier.com/locate/withdrawalpolicy).
For further information see the publishing ethics page at http://www.elsevier.com/publishingethics and the journal home page.

Author representations

- The Article I have submitted to the journal for review is original, has been written by the stated authors and has not been publishe
- The Article was not submitted for review to another journal while under review by this journal and will not be submitted to any oth
- The Article and the Supplemental Materials contain no libellous or other unlawful statements and do not contain any materials tha or proprietary rights of any other person or entity.
- I have obtained written permission from copyright owners for any excerpts from copyrighted works that are included and have cre the Article or the Supplemental Materials.
- Except as expressly set out in this License Agreement, the Article is not subject to any prior rights or licenses, and if my or any of institution has any policy that might restrict my ability to grant exclusive rights under this License Agreement, a written waiver of obtained.
- If I am using any personal details or images of patients or research subjects, I have obtained written permission or consent from t applicable, the next of kin). See http://www.elsevier.com/patientphotographs for further information.
- Any software contained in the Supplemental Materials is free from viruses, contaminants or worms.
- If the Article or any of the Supplemental Materials were prepared jointly with other authors, I have informed the co-author(s) of th Agreement and that I am signing on their behalf as their agent, and I am authorized to do so.

For information on the publisher's access policies, please see http://www.elsevier.com/access.

☑ **I have read and agree to the terms of the License Agreement.**

30th September 2015 T-copyright license-v3/2015

Appendix O Demonstrating the fuzzy cognitive mapping procedure

The fuzzy cognitive mapping procedure is divided into:

I. Coding data (from text) using Wrightson's (1976) technique; then
II. Organizing the coding into an adjacency matrix and plotting the adjacency matrix to create a fuzzy cognitive map; and finally
III. Analyzing the plot and adjacency matrix.

I. Coding data (from text)

The FCM coding process for text is outlined by Wrightson (1976) and summarized as:

1. Is there a relationship? In English grammar, the simplest structure for identifying a relationship in the interview text is: Subject-Verb-Object. This translates into FCM terminology as: cause concept-linkage-effect concept. The interview text is read and the relationships are identified. Each relationship is further coded with steps 2 – 4, one relationship at a time.
2. What is/are the concept(s) in the identified relationship? A concept must be able to take on a value. For example, the term "the process" is not a concept because "the process" does not have a value. The term, "the efficiency of the process" is a concept because efficiency can have a value. Concepts can also be events, where the value is in terms of it occurring or not. Concepts are isolated in the identified relationships.
3. Identify the cause concept and the effect concept (in the isolated concepts in the identified relationship). There are many special cases (e.g. complex cause, complex effect, etc.) that Wrightson (1976) outlines in detail. In general, the following questions are helpful to ask when identifying concepts as either cause or effect:
    a. Does the concept initiate the action (cause concept)?
    b. Does the concept receive the action (effect concept)?
4. What is the link symbol and its (fuzzy) logic value between the cause concept(s) and the effect concept(s) (in the isolated concepts in the

identified relationship)? Wrightson (1976) outlines in detail several special cases. In simplest form, the linkages in Table 17 exist, repeated below. The linkage is coded with a symbol and then the value.

Link symbol	Link value	Link meaning (associated verbs)
+	1	Positively associated with, e.g. by, would, is based on, would be more, want to
-	-1	Negatively associated with, e.g. eliminate, don't have to, no need for, does not require
⊕	0.5	Will not hurt, does not prevent, is not harmful to
⊘	-0.5	Will not help, does not promote, is of no benefit to
a	0	May or may not be related to, affects indeterminately

Table: Fuzzy cognitive map linkage values and meanings (linkages based on Wrightson (1976) and fuzzy logic values based on (Kosko, 1986))

Example of Coded text:

Using the numbered instructions (#1-4) above, and the additional coding rules outlined in §6.2.2.1, the text of #1-4 itself is coded with results in the below table. The codes are generated with the first number being the paragraph number of the source and the letter generally following the order that the code occurred within the paragraph.

Code	Cause Concept	Link	Effect Concept	Code
1A	Subject in English grammar found	+	Cause concept present	1B
1C	Object in English grammar found	+	Effect concept present	1D
1E	Verb in English grammar found	+	Linkage present	1F
1A	Subject in English grammar found	+	Verb in English grammar found	1E
1E	Verb in English grammar found	+	Object in English grammar found	1C
2A	Able to take on a value	+	Isolate concept	2B
-2A	Not able to have a value	-	Isolate concept	2B
2A	Has a temporal quality (occur or not)	+	Isolate concept	2B
2B	Isolate concept	+	Cause concept present	1B
2B	Isolate concept	+	Effect concept present	1D
1B	Cause concept present	+	Action occurring	1E
1E	Action occurring	+	Effect concept present	1D
1E	Verb in text found	+	Link symbol assessed	4A
1E	Verb in text found	+	Link value assessed	4B

Table: FCM coding example from points #1-4

This table highlights many of the coding rules, including structural reversals, chain of events, replacing pronouns, negative linkages and concepts (showing duplicated relationships here), and the merging process. For example, the concepts in point #3 refer to concepts identified in point #1, so they are coded using the preceding codes.

II. Organizing the coding into an adjacency matrix and plotting the adjacency matrix to create a fuzzy cognitive map

The coding (from the above table) is translated into a square adjacency matrix (A). The number of concepts determines the size of the square adjacency matrix (A_{ij}). The cause concepts are represented as rows (i) in the adjacency matrix and the effect concepts are represented as columns (j). Each linkage value is placed in the adjacency matrix (a_{ij}) according to its cause concept (row) and effect concept (column). To illustrate this process, the FCM coding example of the instructions (above table) is shown here as an adjacency matrix. The adjacency matrix is checked to ensure that all nodes are related to at least one linkage; the minimum number of linkages is equal to the number of nodes.

Code	1A	1B	1C	1D	1E	1F	2A	2B	4A	4B
1A	0	1	0	0	1	0	0	0	0	0
1B	0	0	0	0	1	0	0	0	0	0
1C	0	0	0	1	0	0	0	0	0	0
1D	0	0	0	0	0	0	0	0	0	0
1E	0	0	1	1	0	1	0	0	1	1
1F	0	0	0	0	0	0	0	0	0	0
2A	0	0	0	0	0	0	0	1	0	0
2B	0	1	0	1	0	0	0	0	0	0
4A	0	0	0	0	0	0	0	0	0	0
4B	0	0	0	0	0	0	0	0	0	0

Figure: Adjacency matrix from the FCM coding example (above table)

This adjacency matrix from the FCM coding example is plotted using social network visualization software as a di-graph below. Codes (cause and effect concepts) are represented as nodes (circles). The vectors represent the linkages. The size of the node (each circle representing a code) is determined here by its centrality (Equation 14). The centrality of a node is measured as the sum of its in-degree and out-degree (the number of linkages that enter or exit the node respectively). The adjacency matrix is plotted in the following figure.

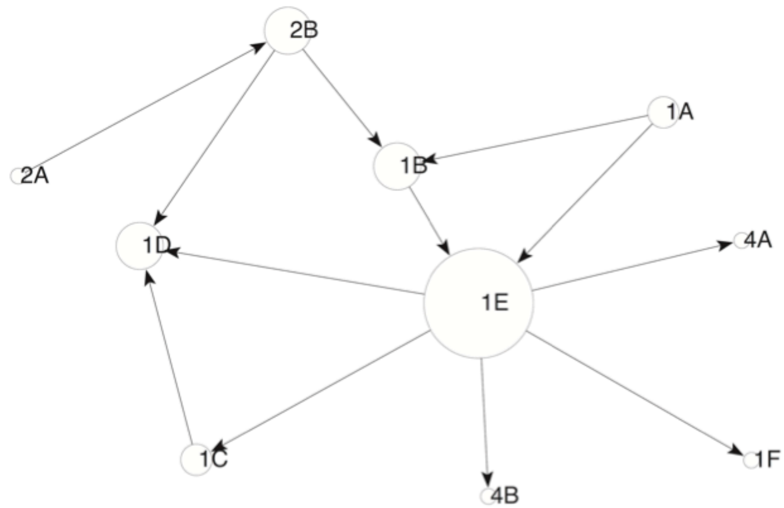


Figure: FCM plot from the FCM coding adjacency matrix (above figure)

III. Analyzing the FCM plot and adjacency matrix

The fuzzy cognitive plot and adjacency matrix are analyzed using Equation 12 to Equation 16, repeated here with their explanations. First, nodes can be categorized as: transmitter variables, receiver variables, or ordinary variables. The variable type is based on calculations for in-degree (id, the number of linkages entering the node) and out-degree (od, the number of linkages exiting the node). If the node only has an in-degree (od=0), the variable is an overall effect (receiver variable). If the node only has an out-degree (id=0), the variable is an overall cause (transmitter variable). If the node has both in-degree and out-degree (id≠0 and od≠0), it is an ordinary variable that plays an overall transitory role as both a cause and an effect relative to different nodes.

The out-degree (od) for each variable is calculated in Equation 12 (Özesmi and Özesmi, 2004, p. 51) by the row sum of absolute values in the adjacency matrix.

$$od(v_i) = \sum_{k=1}^{N} | a_{ik} |$$ Equation 12

The in-degree (id) for each variable is calculated in Equation 13 (Özesmi and Özesmi, 2004, p. 51) by the column sum of absolute values in the adjacency matrix.

$$id(v_i) = \sum_{k=1}^{N} | a_{ki} |$$ Equation 13

The centrality (c) for each variable is calculated in Equation 14 (Özesmi and Özesmi, 2004, p. 51) by the summation of the in-degree and out-degree.

$$c(v_i) = od(v_i) + id(v_i)$$ Equation 14

The adjacency matrix and plot (above figures) are analyzed with Equation 12 to Equation 14 with results in the following table.

Code/node (v_i)	od(v_i)	id(v_i)	c(v_i)	Code/node/variable categorization		
				Transmitter	Receiver	Ordinary
1A	2	0	2	x		
1B	1	2	3			x
1C	1	1	2			x
1D	0	3	3		x	
1E	5	2	7			x
1F	0	1	1		x	
2A	1	0	1	x		
2B	2	1	3			x
4A	0	1	1		x	
4B	0	1	1		x	

Table: FCM analysis from the FCM plot and adjacency matrix (above figures)

The analysis in this table shows that of the ten codes (N=10), 40% are receiver variables (1D, 1F, 4A, 4B); 40% are ordinary variables (1B, 1C, 1E, 2B); and 20% are transmitter variables (1A, 2A). The transmitter variables can be considered useful starting points in the coding process (finding the subject in a sentence and identifying if a concept can take on a value). The receiver variables are conclusions of the coding process (e.g. effect concept present and linkage present). The ordinary variables play a central role throughout the coding process (e.g. cause concept present and isolating concepts). The node with the highest centrality is code 1E (verb or action), which indicates that it is a crucial consideration in the coding process.

In addition, the adjacency matrix and fuzzy cognitive map can be analyzed for its complexity. There have been suggestions to analyze complexity based on the total number of receiver variables (Eden et al., 1992) or a receiver to transmitter ratio (Özesmi and Özesmi, 2004). Other considerations include the number of variables (N) in a map and the number of linkages (L, cf. Equation 15 from (Özesmi and Özesmi, 2004, p. 51)).

$$L = \sum_{i=1}^{N}\sum_{j=1}^{N} | a_{ij}| \qquad \text{Equation 15}$$

After calculating these factors, the interconnectivity of a map can be calculated through its density (D, cf. Equation 16 (Özesmi and Özesmi, 2004, p. 51)). When each node is linked once to every other node with no self-loops, D = 1, indicating a high degree of interconnectivity.

$$D = \frac{L}{N(N-1)} \qquad \text{Equation 16}$$

The adjacency matrix and plot (above figures) are analyzed with Equation 15 and Equation 16. There are 10 codes (N=10) and 12 linkages (L=12), so the density (D) of the fuzzy cognitive map is 0.13 and the map is clear in 2D, so it is not overly interconnected or complex.

Appendix P Participant descriptions of their PD experience

In the second co-design event (PD3 in Chapter 7), the participants were asked: *How would you describe your experience with participatory design?* The individual participant responses to this question are as follows:

"Enjoyed the experience and collaboration between all different employee groups"
"Thought it was very productive"
"We are another step closer"
"Good group involvement"
"Lots of brainstorming"
"Maybe have smaller group with more time, more often"
"Fulltime and students great idea"
"Group discussions work well"
"Liked the different settings – on floor, in meeting room"
"Involving different aspects of thinking, e.g. talking, hands on, etc."
"It's a great idea that we can have a mistake free process."
"I think that some of the full timers won't be ok with this process."
"Its great that we can make this better and easier on our bodies."
"I really liked that we had group discussions because all the big ideas came from everyone feeding on each other's ideas."
"I would have liked to have had more time with multiple products on the ground. By using one product I don't think we tackled the big issues that could arise in the future."
"Very informative"
"Seems like we got a lot accomplished, a lot of ideas out on the table"
"We still need to make things concrete though"
"Progress has been made, we just need to elaborate on some issues"
"I enjoyed the experience, I especially liked being included in the process as an employee, I think employee feedback is very important in the decision making process"
"I think there needed to be more research comparing build times using the old method to build times using the new method with some [assemblies]"
"Great time!"

Vita auctoris

Name:	Victoria Townsend
Place of Birth:	Sarnia, ON
Year of birth:	1980
Education:	Lambton College of Applied Arts and Technology, Sarnia, ON Diploma, Mechanical Engineering Technology, 2003
	Lakehead University, Thunder Bay, ON BEng, Mechanical Engineering, 2005
	University of Windsor, Windsor, ON MASc, Industrial Engineering, 2010