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ORIGINAL PAPER

Fuzzy cognitive modeling with users for design system analysis

Victoria Townsend[1] · **Jill Urbanic**[2]

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Abstract

This paper outlines a fuzzy cognitive mapping (FCM) approach for engaging users in constructing a model for engineering design system analysis. The model's scope is drawn in reference to a socio-technical system and demonstrated with an assembly production system (a socio-technical system archetype). In particular, this paper focuses on modeling an existing assembly production system that needs to be re-designed, then analyzing the system models to inform the re-design task. The modeling approach engages users as participants (18 in this research) in observation and interviews, and these data are coded into adjacency matrices and fuzzy cognitive maps separately then integrated. The ability to model multiple users and technical entities together in breadth and detail, qualitatively and quantitatively, enables designers to zoom in to see the detail and zoom out to see a holistic perspective. The models are analyzed for overall cause, effect, and central variables. Through the FCM analysis of these variables, the elements of the existing design solution are made explicit, including inputs, external and boundary constraints, design principles, outcomes and outputs, function, and operations and structure. This is particularly useful in re-design, as demonstrated in the industrial re-design project here, where the FCM models make the current system design explicit and their analyses inform re-design intent by being synthesized into re-design foci and tasks.

Keywords System analysis · User design · Socio-technical systems · Fuzzy cognitive mapping

1 Introduction

Modeling is critical to engineering design because the information that models offer may be needed at any point in the engineering design process (Pahl et al. 2007). Specifically in the system analysis phase, models are commonly used to examine the behavior of solution variants so that a solution can be selected. System analysis can also be performed on an existing system to make the current design solution and its behavior explicit. In the latter use, these models provide insight to refine a design solution and, more deeply, can inform the intent for re-design, where whole or part of a previous design solution is re-worked to generate a new design (Dixon and Colton 2000). This paper outlines a modeling approach for system analysis with an industrial re-design project: making a current design solution and its behavior explicit, then harnessing this analysis as feedback to define new re-design tasks. This purpose makes this modeling approach valuable to design engineers who seek to learn from, and improve upon, a previous design.

In addition to its purpose, a good model must clarify what it represents and how it represents it; the former refers to the model's scope and contents, the latter its mode of communication. The former is addressed here in this introduction, generally then specifically in the context of the research presented. The latter, the fuzzy cognitive modeling approach, is addressed in Sect. 2.

In engineering design, a model generally represents an abstraction of reality that serves as a cognitive tool (Goel and Helms 2013). The model's boundary can be drawn at various degrees of scope, impacting what the model's contents will include. When modeling a design and its behavior in system analysis, where the line of scope is drawn can position users within or outside of the model. At a micro level, the model could include a rack and pinion inside a machine

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✉ Victoria Townsend
townsenv@gmail.com

Jill Urbanic
jurbanic@uwindsor.ca

[1] Department of Applied Research and Development, St. Clair College, 2000 Talbot Rd. W., Windsor, ON N9A 6S4, Canada

[2] Department of Mechanical, Automotive, and Materials Engineering, University of Windsor, 401 Sunset Ave., Windsor, ON N9B 3P4, Canada

(a mechanical system). At a more macro-level, the model could include the machine and its user(s) (a user-machine system). At an even greater macro-level, the context could include a set of multiple users and their machines operating an assembly production system together (a socio-technical system) and so on.

As the scope for the boundary is drawn wider, the system model involves increasing consideration for users in tandem with additional and diversified system entities and connections. As this interconnected system design grows, the system behavior becomes more uncertain because users exercise choice and multiple users working together exhibit social relations. As a result, the potential for multiple solutions, under-constrained systems, and ill-defined problems is more likely. At the same time, this interconnected system poses an opportunity to assess design use, behavior, and re-design more comprehensively. Accordingly, the need for a system model to assist in system analysis intensifies as the scope of the system model is drawn wider.

This need is further clarified here with the industrial re-design project addressed in this paper. This project involved re-designing an assembly production system where two builders at a time manually assemble over 396 final product variants with the use of tools and machines in a fixed product layout. The operators (builders) are temporarily assigned to the position, so the teams are consistently changing. Additional users of the assembly production system included the roles of lead hand, supervisor, planner, and manager. It is clear that the multiple users of this system can offer valuable input to the design process towards clarifying first how they use the system and how it operates and, in turn, how it is not working and can be improved through re-design. Typically, these types of systems are re-designed by addressing one factor at a time and continuously improving; however, the question is—what factor is most critical to address in the re-design task? If a designer asked each user for their perspective, they are likely to differ based on their various roles. Often times the decision is made by management or an engineer who is in the position of designer. Developing a system model with user input (manager and non-manager) positions the engineering designer as a facilitator to analytically define the re-design task based on analyzing the system model, which harnesses the collective knowledge of all users and provides robust rationale for the decision. In this systems approach, it is also possible to identify synergistic factors that can be re-designed together. Accordingly for this project, system analysis was performed with the system users to create a model of the existing production system in use (characterizing its behavior), then the analysis of this model was further synthesized into re-design tasks.

This focus is consistent with calls for user-centered approaches to engineering design as a whole (Stappers et al. 2007) and specifically integrating users into research on engineering design systems to better understand how people use designs (Piela et al. 1992). There is a broad body of literature on user evaluations in product design, and positive impacts on assembly have been noted (Sundin et al. 2004). In engineering design, users have been involved in participatory design mostly in regard to ergonomics (Sundin 2003; Laing et al. 2005, 2007), with demonstrated positive outcomes on worker comfort and productivity (Vink et al. 2006). User engagement in modeling has included sketching for design problem analysis (Römer et al. 2000) and behavioral modeling for design validation (Malak and Paredis 2007). The engineering design literature does not address how users can directly participate in system analysis modeling when re-designing socio-technical systems, which is the contribution of the paper presented here. By addressing this need, this paper also aligns with the emphasis that because engineering design models are cognitive constructs it is critical that a "shared understanding is constructed through social processes of discussion and clarification" (Eckert and Stacey 2010; Chakrabarti and Blessing 2014). This takes place here with users in constructing a system model.

The integral role of users in operating systems, such as assembly production systems, is defined as socio-technical systems (STS), which have been examined in the engineering design literature in numerous contexts. They have been applied to product design (Gish and Hansen 2013; Fernandes et al. 2014) and systems design more broadly (Zhao and Steier 1993; Naumann et al. 2011; Jones et al. 2013). They have been related to various stages of the engineering design process, such as requirements analysis (Sutcliffe 2000), prototyping (Kember and Murray 1988), and implementation (Zhao et al. 1992; Panebianco and Pahl-Wostl 2006). They have been related to additional design methodologies, such as co-design (Clancey 1993) and collaborative design (Lu and Cai 2001; Jing and Lu 2011). STSs have also been related to engineering design holistically in themes of sustainability and life-cycle performance (Cardin et al. 2013; Hu and Cardin 2015), innovation (Legardeur et al. 2010), knowledge (Clancey 1993; Baxter et al. 2007), best practices (Stevenson et al. 1994), and decision making (Brissaud et al. 2003; Ostrosi et al. 2011). This paper contributes to this literature with an approach for modeling a STS for system analysis and subsequent re-design.

The research presented here answers the following research questions: how can a socio-technical system model of an existing system be built with users for system analysis? How can this inform engineering re-design, especially the re-design task? To examine these questions, modeling is first discussed and specifically fuzzy cognitive modeling (FCM) used in this research. The research methodology is then outlined, including the field study design context and fuzzy cognitive mapping technique. Next, the results and analysis are presented, featuring the fuzzy cognitive models of the system design. The discussion interprets the specific fuzzy cognitive models generally in terms of Lin and Zhang (2004) and Zhang et al.'s (2011) 'unified' engineering system design model, so that the specific results of the industrial re-design project can be understood more broadly and related to re-design considerations, especially to re-design tasks. The re-design tasks from the industrial field study are then aligned with participants' re-designs. Trustworthiness and validation are then discussed with limitations, benefits, and contributions followed by conclusions. This flow is illustrated in Fig. 1.

2 Modeling with fuzzy cognitive mapping

Models used in engineering design can be descriptive or predictive; deterministic or non-deterministic; iconic, analog, or symbolic (Dieter and Schmidt 2008). This paper focuses on creating a descriptive, non-deterministic, and empirically symbolic model to address the aforementioned challenges. Descriptive models explain a real-world phenomenon as a system, providing critical insight into the design behavior. Non-deterministic models describe a system with ill-defined problems, managing "incomplete task descriptions and non-deterministic solution paths" (Hayes 1989). A symbolic model built on empirical evidence is critical to making the many system entities and connections explicit, especially the human aspects in a socio-technical system that cannot be derived from scientific rules as they are based on personal experience and localized social norms.

Existing engineering design approaches for system modeling and analysis with multiple stakeholder inputs are restricted in this respect. Value-driven design aims to "convey the true preferences of the stakeholder using mathematical formulations like value models", such as Topcu and Mesmer's value models (2018); this value model example is strong on analysis but has limited flexibility and breadth of stakeholder input since the majority direct their preferences towards a primary stakeholder's preference. Other approaches to design system modeling and analysis emphasize flexibility in stakeholder input, such as the KJ method, which clusters ideas; this method is strong on flexible input but has limited system analysis because it does not examine how clusters relate to one another. More broadly, analytical engineering design methods such as those summarized by Wynn and Clarkson (2018), could be adapted for participant input but require structured inputs needing translation between design and stakeholder languages (e.g., system dynamics) and have limited system scope (e.g., process flowcharts). What is needed is a means of flexible stakeholder input coupled with rigorous system analysis with the required breadth (macro) and depth (micro) for modeling and analyzing a socio-technical system for engineering re-design. To unite these qualities, the authors considered logic as a common language and starting point. In searching further, Fuzzy Cognitive Mapping (FCM) was identified as a potential tool since it identifies concepts and their relationships, capable of capturing a broad variety of user inputs while providing a logical foundation for system analysis. To support maximum flexibility in user input, these relationships and concepts were extrapolated from interviews and observations with users, providing freedom for users to say (designers to listen) and users to do (designers to observe) relative to the system under investigation. This flexibility in input and analysis structure also offers the potential to discover things that the users and designers did not expect, a potential "ah ha". What has resulted is a broadly applicable method for modeling system analysis with users that provides design engineers with the rigorous analysis they need to understand socio-technical concepts and relationships while providing users with freedom of expression,

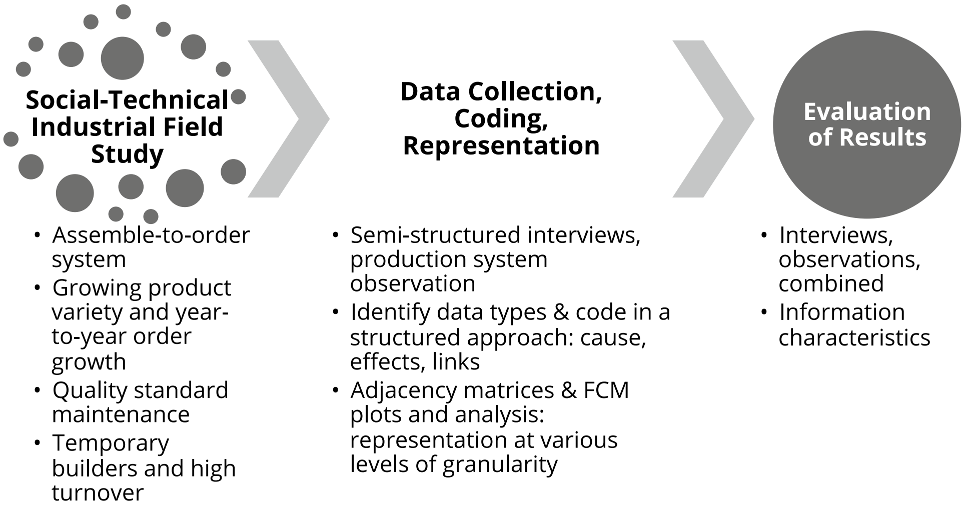


Fig. 1 Research process flow

thus contributing to the model's ability to represent reality and discover emergent insights into a system and its re-design.

Current FCM progress in engineering has been summarized by Papageorgiou (2014). 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. Thus far, the FCM approach has had limited use in engineering design, applied in the context of environmental planning (Borri et al. 2015), manufacturability analysis (Gavankar and Rao 1995), virtual modeling in the industrial design of automobiles (Silva 1996), failure analysis (Augustine et al. 2012), new product development (Achiche et al. 2013), consensus in the design process (Ostrosi et al. 2011), and assembly design decision making (Kim et al. 2008). The application of fuzzy cognitive mapping to modeling socio-technical systems in system analysis made in the research presented here relates this advancement in knowledge engineering to engineering design and does so with the following methodology.

A cognitive map consists of causal relationships (linkages) between concepts (causes and effects). Visually, the map is drawn as a di-graph, with linkages depicted as vectors and concepts as nodes (as presented in Fig. 2). Fuzzy cognitive maps allocate fuzzy logic values to the vectors so that the importance of the node can be analyzed. FCM is advantageous in organizing big data and representing knowledge depth and connectivity (Papageorgiou 2014). The ability to model multiple users and technical entities together in breadth and detail makes FCM quite useful for modeling in system analysis.

3 Methodology

This research was conducted in an industrial field study, where an industrial assembly production system design was modeled with its users. This type of system was selected because it is a socio-technical system archetype (Cherns 1989; Emery 1989), involving multiple users working in tandem with technical entities (machines, tools) and one another to operate the system (Vermaas et al. 2011). As such, it provides a rich proof of concept for the proposed approach of system modeling with users that can be simplified for systems of smaller scope (e.g., one user and a product).

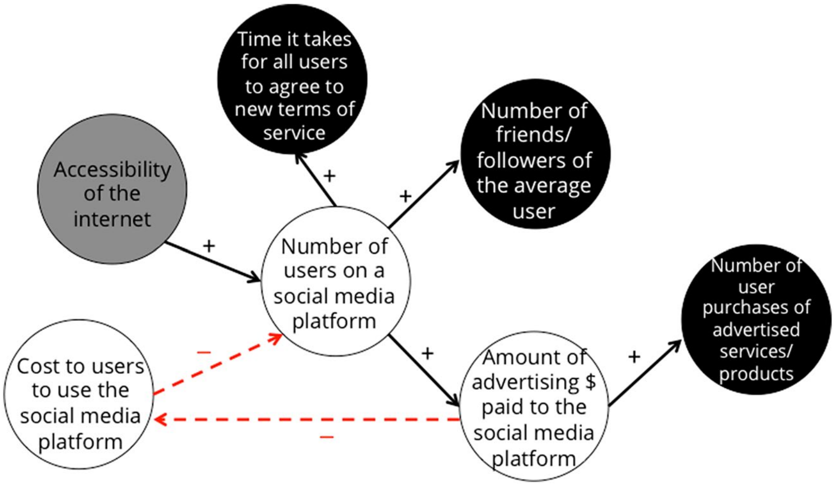
The assembly production system studied was an assemble-to-order system. The re-design problem was to improve the performance of the system design to:

- Address growing product variety (396+ final assembly variants);
- Address growing orders (25.5% year-to-year order growth from 2003 to 2012);
- Maintain quality standards;
- Accommodate for a high turnover of temporary employees; and
- Reduce cycle time.

This problem is increasingly more common in the growing paradigm of mass customization (Koren 2010). The primary outcome of the system analysis modeling here is to clarify the re-design tasks.

In this assemble-to-order system, each final assembly consisted of 27–79 total components of 5 main types. The final assembly was manually assembled in batch production using a fixed product layout. Two builders, builder A and builder B, assembled the final products with rigid and flexible components. The builder position was assigned

Fig. 2 A simple fuzzy cognitive map (modeling a social media platform socio-technical system with user involvement in mind)



on a temporary basis to temporary, part-time, or full-time employees. The production environment was unionized. The users of the system involved as participants in the study pertained to the roles of builder, lead hand, planner, supervisor, and manager. In total, 18 participants in these management and non-management roles took part in the research presented here. Since temporary workers were included, recruitment was ongoing; thus, 8 participants (of all 5 roles) took part in the first data collection method (interview) and an additional 10 participants took part in the second data collection method (observation). For further details on the participant demographics and technical context, please refer to Townsend (2015). All participants were recruited in line with research ethics protocols. Once the participants were recruited, the fuzzy cognitive mapping process was applied.

The general process for creating a fuzzy cognitive map consists of collecting data; coding the data into cause, linkage, and effect relationships; arranging the coding into an adjacency matrix; and then plotting the adjacency matrix as a di-graph where cause and effects are nodes (ellipses) and the linkages are a vector. A simple fuzzy cognitive map is illustrated in Fig. 2 for modeling a social media platform socio-technical system with user involvement in mind. The nodes (ellipses) indicate overall cause concepts (gray filled ellipse), overall effect concepts (black filled ellipses), and central concepts that act as intermediary cause and effect (white filled ellipses). The vectors indicate negative linkages (red dashed arrow) and positive linkages (black solid arrow).

An overview of the fuzzy cognitive mapping process that was utilized in this research is illustrated in Fig. 3. What is unique about the process used here, compared to the general FCM process, is that both interview and observation data were utilized and then integrated into one fuzzy cognitive map.

The steps in Fig. 3 are described in more detail in the subsequent sections.

3.1 Data collection

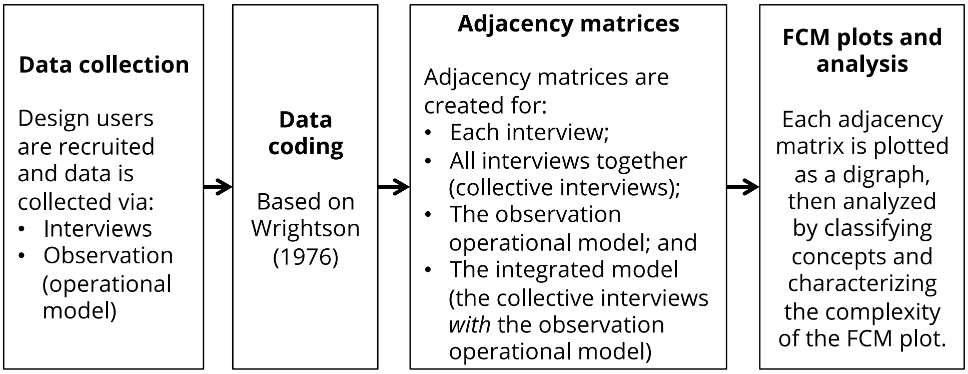
The participants were asked to participate in semi-structured interviews and observations. Semi-structured interviews were conducted with participants, then recorded, transcribed, and verified. Participants were asked (1) how would you describe the current assembly process? (2) How would you describe 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? These questions are open ended and general to enable the unique perspectives of users to be shared. Any follow-up questions to a participant response generally asked the participant to clarify a concept that s/he mentioned or paraphrased the question if it was unclear to a participant. An example of a clarification is a participant mentioned "mistakes" and the interviewer asked "and the mistakes are what you're finding when you're doing those checks?" An example of paraphrasing is when the interviewer asked the participant, "How would you describe your work with the current assembly process?" and the participant said "good". The interviewer further inquired by asking, "How would you describe the things that you do in order to build [an assembly]?"

Observations of the participants operating the production system were conducted at random time intervals. Ten unique datasets (production runs) of 226 unique data members (assembly cycles) were collected, which provided information on the products, process steps, and layout. These data were integrated into an observation operational model using statistical tests (Welch's ANOVA and regression). The observation operational model is further described and defined by equations in the results Sect. 4.2. After data collection, the data were coded.

3.2 Data coding

In fuzzy cognitive mapping, data can be coded from questionnaires (Roberts 1976), by participants in an interview (Carley and Palmquist 1992), from interview texts

Fig. 3 The fuzzy cognitive mapping process used in this research



(Wrightson 1976) or through data (Schneider et al. 1998). The last two methods were utilized in this paper.

The main goal of the coding is to identify concepts and their relationships in the form of cause concept/linkage/effect concept. A ‘cause’ is defined 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.

Each interview transcript was coded one sentence at a time, and each observation was coded one equation at a time. The coding process outlined by Wrightson (1976) is summarized in Fig. 4, with further details and special considerations for data in the form of interview text and an observation operational model specified in Table 1.

Additional considerations for the coding are available in Wrightson’s (1976) coding summary; for further details in relation to the industrial re-design project here, please see Townsend (2015).

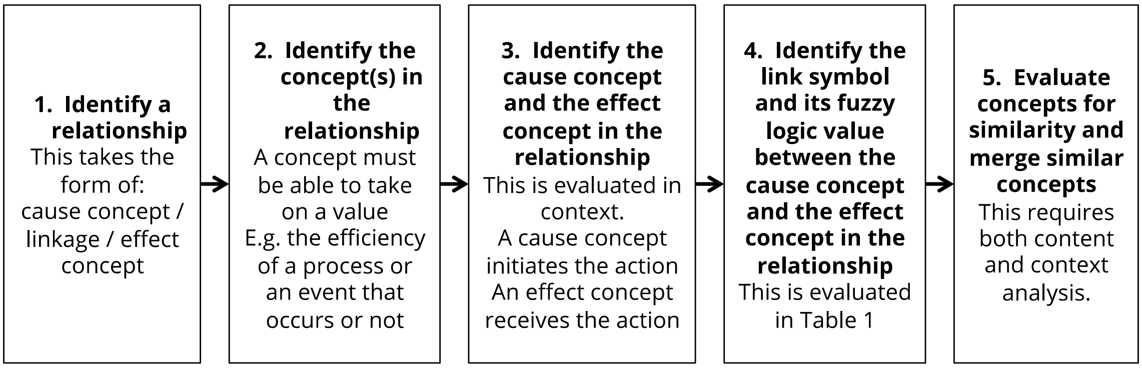


Fig. 4 Summary of Wrightson’s (1976) FCM coding process

Table 1 FCM coding considerations for interview and observation model data

Wrightson’s (1976) coding process	Interview text (Wrightson 1976)	Observation model
1. Linkage	Verb	=
2. Concepts	Noun with qualifiers. The concept must be able to take on a value. E.g., the efficiency of the process (not just the process)	Variable or group of interdependent variables
3. Cause concept	Subject	Independent variable
3. Effect concept	Object	Dependent variable
4. Linkage symbol and value + 1	Strong positive association, e.g., by, would, is based on, would be more, want to, etc.	=, *, +
− 1	Strong negative association, e.g., eliminate, do not have to, no need for, does not require, etc.	/, –
⊕+ 0.5	Tentative positive association, e.g., will not hurt, does not prevent, is not harmful to, etc.	Not applicable
⊘− 0.5	Tentative negative association, e.g., will not help, does not promote, is of no benefit to, etc.	Not applicable
a	Indeterminate association, e.g., may or may not be related to	Not applicable
5. Merging similar concepts	Does the speaker make a distinction between the two concepts? If so, keep the concepts separate	Do the variables measure different things? If so, keep the concepts separate
	Would the speaker believe that the logic had been distorted if the concepts were merged? If so, keep the concepts separate	Would logic be distorted if the concepts were merged? If so, keep the concepts separate
	Is an antonym used? There should be one concept for a noun and its antonym and synonym	Is there an inverse variation of the variable? There should be one concept for a variable and its inverse variation

After each interview text was coded, as well as each equation in the observation operational model, the codes between them were compared and merged to create the integrated interview and observation model. This was done with the following rules adapted from Table 1:

- Does the participant make a distinction between the two concepts 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? There should be one concept for a synonym and antonym.

If one concept from the interview described several concepts in the observation model, or vice versa, they were related with a bi-directional linkage since they were related in meaning but not the same, and one is not necessarily the cause of the other. The same is true if a concept in one partially, but not fully, described a concept in another. The results of this integration are presented later in Table 3. After the data were coded, they were organized into adjacency matrices.

3.3 Adjacency matrices

The coding was translated into a square adjacency matrix (A) of size N, where N is the total number of concepts. Each linkage fuzzy logic value was placed in the adjacency matrix (a_{ij}) according to its cause concept (row) and effect concept (column).

For the interview data, an adjacency matrix was created for each interview ($A_{\text{interview}}$). In this study, there were eight interviews ($A_{\text{interview1}} \ldots A_{\text{interview8}}$). These individual interview matrices were then integrated into one matrix ($A_{\text{interview(all)}}$). Since one interview can contain the same concept that is expressed in another, the two matrices were integrated (rather than summed) interview-to-interview. The integration process started with the first interview adjacency matrix ($A_{\text{interview1}}$). Concepts in $A_{\text{interview2}}$ that differed from $A_{\text{interview1}}$ were added as rows and columns to $A_{\text{interview1}}$ to form $A_{\text{interview1–2}}$. Linkage values from $A_{\text{interview1}}$ remained and linkage values from $A_{\text{interview2}}$ were placed in their corresponding locations in $A_{\text{interview1–2}}$. Redundant linkage values were compared (not added). This checked for consistency in the coding process and across participant data; if there were any discrepancies, the interview transcripts were reviewed to see if there was a coding error or to analyze the participant data. In this study, interview1 was integrated with interview2 into $A_{\text{interview1–2}}$, which was then integrated with interview3 into $A_{\text{interview1–3}}$, and so on until $A_{\text{interview1–8}}$ (which is $A_{\text{interview(all)}}$).

For the observation operational model, an adjacency matrix was created for each equation. In this study, there were eight equations presented in Sect. 4.2. These eight adjacency matrices were then integrated into one matrix ($A_{\text{observation}}$). The integration process started with the first equation adjacency matrix. Concepts in the second equation adjacency matrix that differed from the first were added as rows and columns, and so on for all seven matrices, creating the final integrated matrix ($A_{\text{observation}}$).

For the integrated collective interviews and observation operational model, an adjacency matrix was created. Concepts in the observation operational model ($A_{\text{observation}}$) that differed from the collective interviews ($A_{\text{interview(all)}}$) were added as rows and columns, creating the integrated adjacency matrix ($A_{\text{interview(all)\&observation}}$). After the adjacency matrices were created, they were plotted.

3.4 FCM plots and analysis

The adjacency matrices (A) were plotted as di-graphs using social network visualization software (Pajek 2018) to create the related fuzzy cognitive maps. In the plots, the vector direction travels from the cause node to the effect node. Here, a negative vector was defined with a red dashed line; a positive vector was defined with a black solid line. Nodes were defined as ellipses with diameters relative to their centrality value, which is defined in Eq. 3.

The fuzzy cognitive maps were then analyzed in terms of their structure by understanding each node as a transmitter, receiver, or ordinary variable (v) based on in-degree (id) and out-degree (od) values. Using the FCMapper software (FCMapper 2018) helped to automate this process. A receiver variable (overall effect) has an out-degree of 0 and a non-zero in-degree. A transmitter variable (overall cause) has an in-degree of 0 and a non-zero out-degree. An ordinary variable has a non-zero in- and out-degree. In-degree and out-degree were calculated in Eqs. 1 and 2 from (Özesmi and Özesmi 2004). Based on the in-degree and out-degree values, the centrality (c) for each variable was also calculated (Eq. 3). Additionally, the number of linkages (L, Eq. 4) was also calculated:

$$\mathrm{od}\left(v_i\right) = \sum_{k=1}^{N} |a_{ik}|, \tag{1}$$

$$\mathrm{id}\left(v_j\right) = \sum_{k=1}^{N} |a_{kj}|, \tag{2}$$

$$c\left(v_i\right) = \mathrm{od}\left(v_i\right) + \mathrm{id}\left(v_i\right), \tag{3}$$

$$L = \sum_{i=1}^{N} \sum_{j=1}^{N} \left|a_{ij}\right|. \tag{4}$$

The results for the data collection, coding, adjacency matrices, and FCM plots are presented in Sect. 4. The FCM analysis is shown in Sect. 5.

4 Results

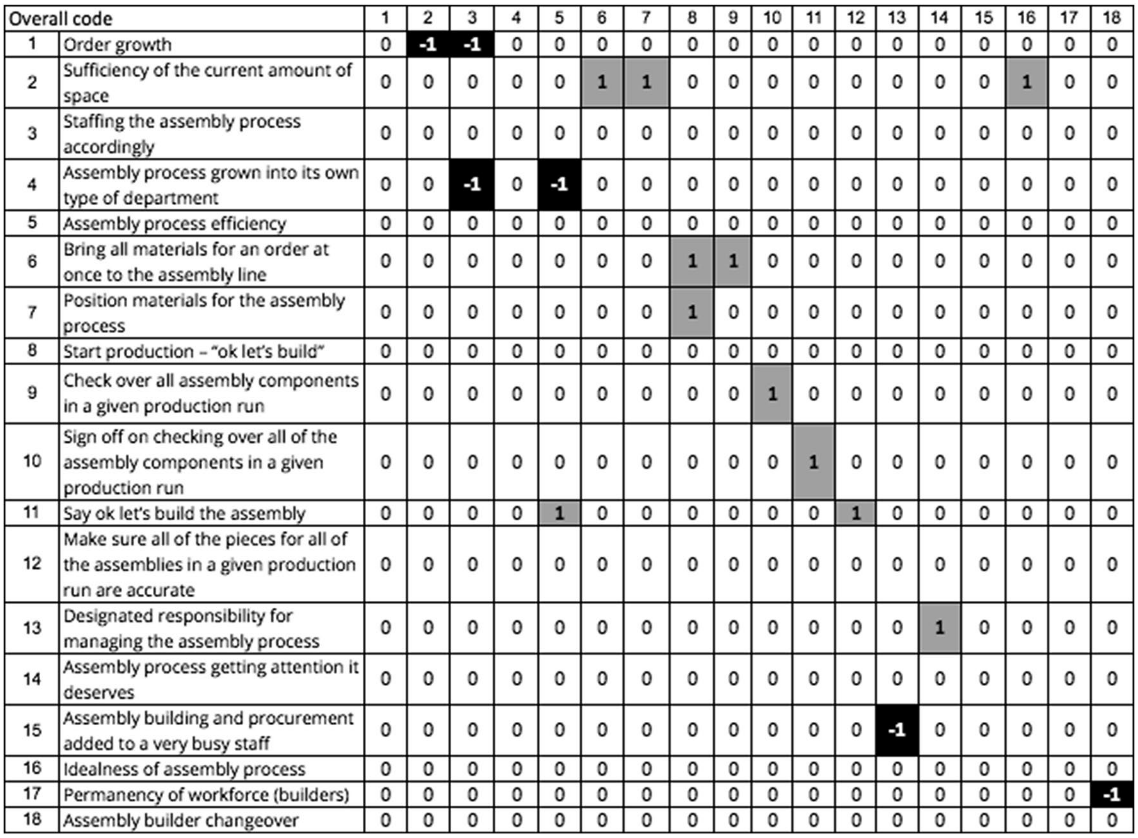
4.1 Interview results

Eight interviews were coded resulting in 247 codes before merging and 120 unique codes after merging, numbered 1–120. Since the interview texts were detailed, this variety of codes (concepts) is in line with Wrightson's (1976) statement: "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). The pre-interview text was specific here since workers were explaining their work in an assembly production system where work was specialized and the participant pool represented a range of roles. A sample excerpt of an interview transcript and coding is presented in "Appendix A", with the corresponding adjacency matrix in Fig. 5 and plot in Fig. 6.

As shown in Fig. 5, FCM matrices are not symmetrical since some but not all cause and effect coding relationships are reciprocal. For example, consider the first coding relationship in the first row of the table in "Appendix A". When the order size grows it has a negative association with the current amount of space because the existing space becomes more crowded. The amount of space does not dictate the order size.

Additional fuzzy cognitive maps from the interviews are shown in "Appendix B". All interview codes are in "Appendix C". Each interview contributes perspectives to the system model. For example, two code summaries are shown in Fig. 7, with their centrality, in-degree, and out-degree values for each interview.

In Fig. 7, code 16 (idealness of the assembly process) is present in each interview as an overall effect (no out-degree) with different codes leading to it. In other words, each participant can think of different concepts to effect improvement. Code 17 (permanency of the workforce) is present in only 4 of the 8 interviews, meaning it is relevant to some users but not others, and it acts as an overall cause (no in-degree) influencing the system. Figure 7 also highlights that the centrality of a code in an interview is the sum of the in-degree and out-degree—only in-degree for an overall effect (code 16) and only out-degree for an overall cause (code 17).



Overall code		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
1	Order growth	0	-1	-1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
2	Sufficiency of the current amount of space	0	0	0	0	0	1	1	0	0	0	0	0	0	0	0	1	0	0
3	Staffing the assembly process accordingly	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
4	Assembly process grown into its own type of department	0	0	-1	0	-1	0	0	0	0	0	0	0	0	0	0	0	0	0
5	Assembly process efficiency	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
6	Bring all materials for an order at once to the assembly line	0	0	0	0	0	0	0	1	1	0	0	0	0	0	0	0	0	0
7	Position materials for the assembly process	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0
8	Start production – "ok let's build"	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
9	Check over all assembly components in a given production run	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0
10	Sign off on checking over all of the assembly components in a given production run	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0
11	Say ok let's build the assembly	0	0	0	0	1	0	0	0	0	0	0	1	0	0	0	0	0	0
12	Make sure all of the pieces for all of the assemblies in a given production run are accurate	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
13	Designated responsibility for managing the assembly process	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0
14	Assembly process getting attention it deserves	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
15	Assembly building and procurement added to a very busy staff	0	0	0	0	0	0	0	0	0	0	0	0	-1	0	0	0	0	0
16	Idealness of assembly process	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
17	Permanency of workforce (builders)	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	-1
18	Assembly builder changeover	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

Fig. 5 Interview adjacency matrix ($A_{\mathrm{interview1}}$)

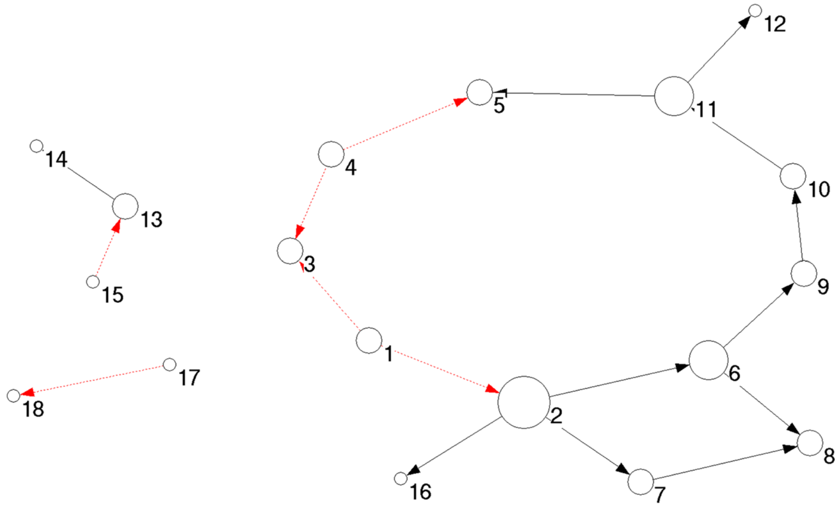


Fig. 6 Interview1 fuzzy cognitive map

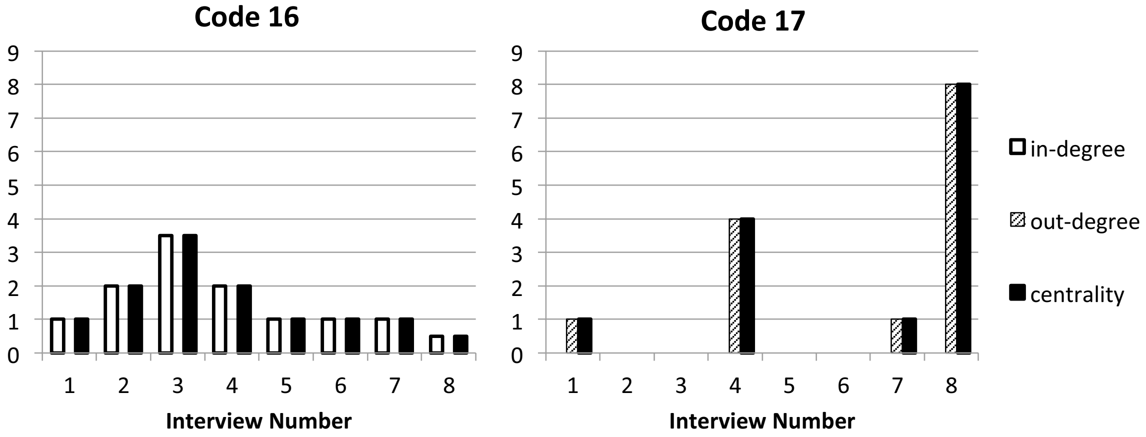


Fig. 7 Code 16 and 17 summary of centrality, in- and out-degree values

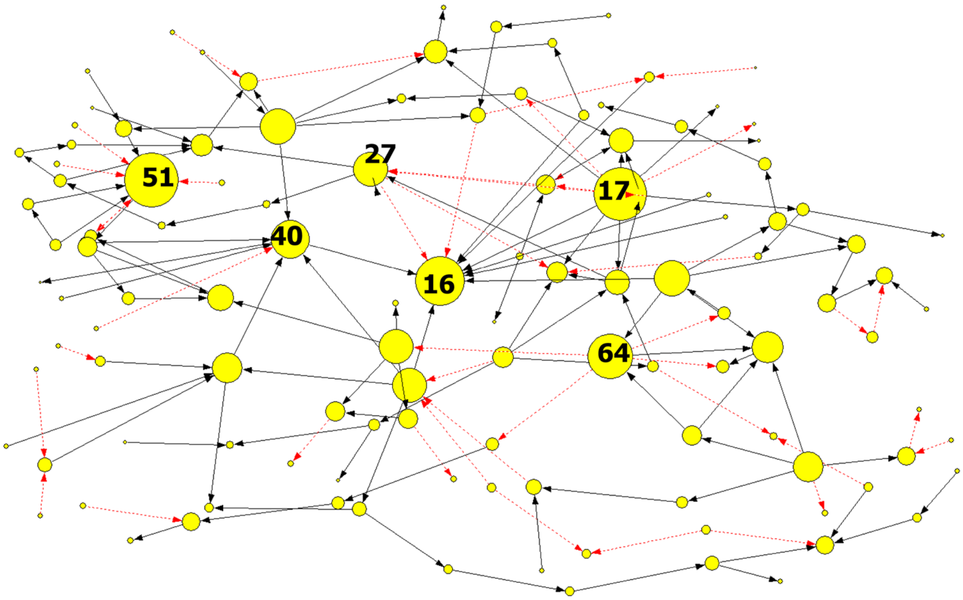


Fig. 8 Collective interview fuzzy cognitive map (codes 16 and 17 highlighted as nodes)

After each interview was mapped individually, they were merged interview-to-interview. The mergence of Interviews 1–3 into a FCM plot is illustrated in "Appendix B" (Fig. 16), which also highlights code details. Figure 8 illustrates the mergence of Interviews 1–8 (collective interviews) into a FCM plot. This model highlights how succinctly the FCM method synthesizes information from multiple user perspectives, versus a code-by-code analysis (Fig. 7), making the critical areas visibly obvious from node size and vector clusters. In Fig. 8, the in- and out-degree are visible as vectors and centrality is visible as node size.

Figure 8 highlights why modeling is critical in re-designing the socio-technical system, because there are many concepts interacting. Without modeling, and without the insight of the user, it would be very difficult to identify all these concepts and their relations. These concepts and relations are critical to re-designing socio-technical systems since they are living systems and re-design involves transforming the system with existing concepts and relations. The observation results provide additional data to consider.

4.2 Observation results

Equations 5–12 outline the observation operational model, which was previously derived from statistical tests (Welch's ANOVA and regression) on the same observation dataset in the same case study. For example, the correlation between mean cycle time and an observation complexity ratio (r) was tested with linear regression, performed with a 95% degree of confidence (R-sq value = 0.81217). The result is shown in Eq. 5. The normality of the mean cycle times was confirmed with a probability plot and fat pencil test. For information on the derivation of the formulas, along with the statistical tests, results, and validation please see Townsend and Urbanic (2015). The focus of the research presented here is to show how a numerical model and its constituent equations that were derived from observation can be used in fuzzy cognitive mapping and related to the interview data.

$$\text{mean cycle time} = 1.2099r + 1.0333, \tag{5}$$

$$r = V + \mathrm{PC} + |\mathrm{DR}| + |\mathrm{TR}| + |\mathrm{PR}| + |\mathrm{AR}|, \tag{6}$$

$$V = 1 - \frac{n}{2\mathrm{Vol}_{\max}}, \tag{7}$$

$$V = \frac{n}{2\mathrm{Vol}_{\max}}, \tag{8}$$

$$|\mathrm{DR}| = \frac{|\mathrm{DA} - \mathrm{DB}|}{\mathrm{DT}}, \tag{9}$$

$$|\mathrm{TR}| = \frac{|\mathrm{TA} - \mathrm{TB}|}{\mathrm{TT}}, \tag{10}$$

$$|\mathrm{PR}| = \frac{|\mathrm{PA} - \mathrm{PB}|}{\mathrm{PT}}, \tag{11}$$

$$|\mathrm{AR}| = \frac{|\mathrm{AA} - \mathrm{AB}|}{\mathrm{AT}}, \tag{12}$$

where

r: observation complexity ratio
PC: pallet count accounts for the number of finished assemblies that will fit on one pallet (relative size of the finished assembly)
V: production phase variable. The observations relate to a production phase (V) in terms of the number of observations taken in the production run (n) and the position of the observations relative to the start of a production run (Eq. 7) or end of a production run (Eq. 8). The logic of using these equations is included in the FCM using the variable 'S' to indicate "start of a production run" (and correspondingly, $-S$ to indicate the "end of a production run") and so S has relevance to the FCM but does not have a corresponding calculation.
$\mathrm{Vol}_{\max}$: maximum total number of final assemblies required to complete the order (i.e., production run volume)
n: observation sample size
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 that refers to the number of distinct component types in an assembly. The number of different components is distributed between builder A and builder B (DA + DB).
TR: distribution of work ratio related to the total number of components
TA: number of total components that builder A handles (for one final product assembly)
TB: number of total components that builder B handles (for one final product assembly)
TT: number of total components in the final product assembly. The number of total components is distributed between builder A and builder B (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 that refers to selecting the components. The number

of picking tasks is distributed between builder A and builder B (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 that refers to combining and positioning the selected assembly components. The number of assembling tasks is distributed between builder A and builder B (AA + AB).

The main purpose of these equations is to understand how the assembly system organizes division of work (DR, TR, PR, AR) relative to builder A (DA, TA, PA, AA) and builder B (DB, TB, PB, AB) to assemble a final product (DT, TT, PT, AT, PC) for a given order and production run (Vol_{max}) relative to an observation set (*n*). The relationship between these variables is synthesized into a complexity ratio (*r*) that correlates with the mean cycle time—when complexity increases so does mean cycle time. To lower mean cycle time, the assembly system needs to be re-designed to lower the complexity ratio (*r*).

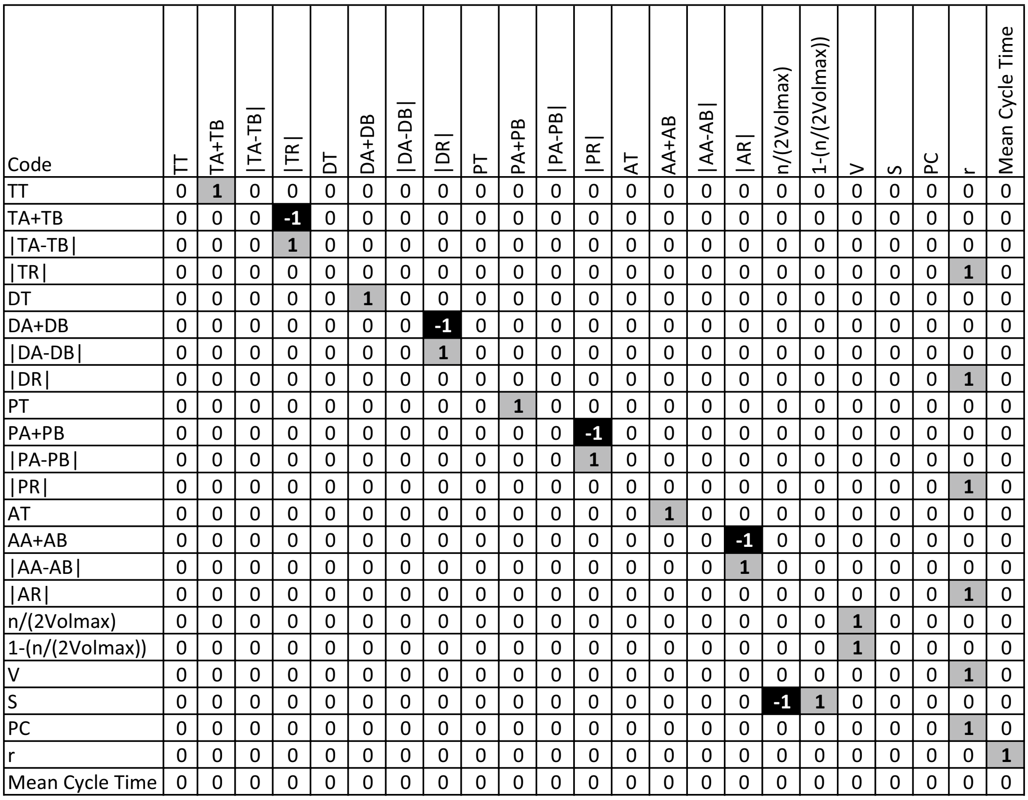
Table 2 Observation operational model sample coding

Cause concept	Link	Effect concept
DT	+ 1	(DA + DB)
(DA + DB)	− 1	|DR|
|DA − DB|	+ 1	|DR|

A sample of the coding for variable DR from this operational model (Eq. 9) is presented in Table 2. Note that DA and DB are grouped together because the terms are interdependent, e.g., if DA increases then DB decreases. As a logic check, the coding in Table 2 shows that the total number of components affects how many components builder A and builder B will have to work with. When this division of work is more even, \|DA − DB\| will decrease, so will DR, then *r*, then mean cycle time. This makes logical sense.

Figure 9 presents the adjacency matrix for the observation model, which is plotted as a fuzzy cognitive map in Fig. 10.

The fuzzy cognitive map from the observation (Fig. 10) contains far fewer nodes than the fuzzy cognitive map from the collective interviews (Fig. 8), nearly 1/5. The observation map had 23 unique codes while the collective interview map had 120 unique codes. To assess if the maps contain the same codes, or different, the coding is compared and then merged where appropriate so that the maps can be integrated.



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

Fig. 9 Observation operational model adjacency matrix ($A_{\text{observation}}$)

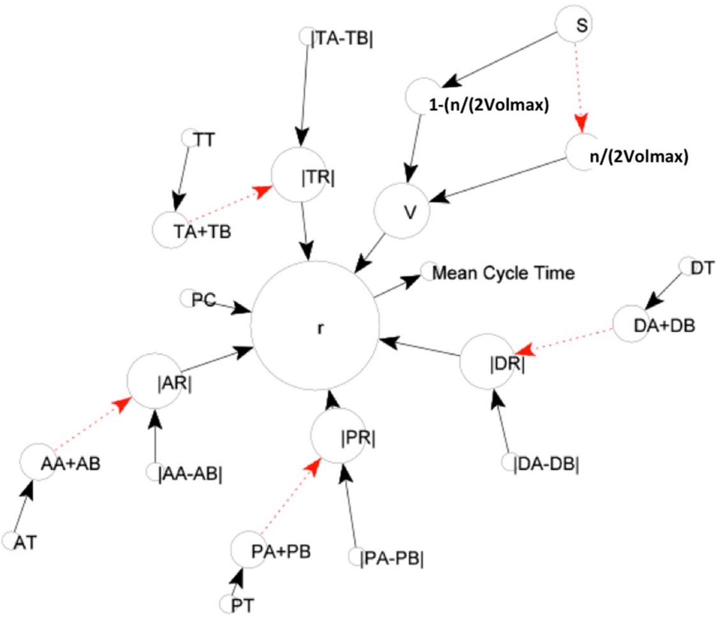


Fig. 10 Observation operational model fuzzy cognitive map

4.3 Integrated (interview with observation) results

Table 3 outlines how the collective interview codes were merged with links to the observation codes.

Figure 11 illustrates the linkages and merging from Table 3. All the concepts from the observation adjacency matrix ($A_{\text{observation}}$) are shown in aqua (dark shading) and the concepts from the collective interview adjacency matrix

Table 3 Linkages between the collective interview and observation FCMs

Collective interview concept (code)	Link	Observation concept (code)
Builders dividing work evenly (20)	-1	$\lvert TR\rvert$
	-1	$\lvert DR\rvert$
	-1	$\lvert PR\rvert$
	-1	$\lvert AR\rvert$
Even out the number of products on each side of the table (42)	-1	$\lvert TA-TB\rvert$
	-1	$\lvert DA-DB\rvert$
Coordinated actions between builders (83)	-1	$\lvert PR\rvert$
	-1	$\lvert AR\rvert$
Being able to position materials for the assembly process (7)	-1	$\lvert TA-TB\rvert$
	-1	$\lvert DA-DB\rvert$
	-1	$\lvert PA-PB\rvert$
	-1	$\lvert AA-AB\rvert$
Having a designated position for materials around the table (45)	-1	$\lvert TA-TB\rvert$
	-1	$\lvert DA-DB\rvert$
	-1	$\lvert PA-PB\rvert$
	-1	$\lvert AA-AB\rvert$
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)	$+1$	$1-(n/(2\text{Vol}_{\max}))$
	-1	$n/(2\text{Vol}_{\max})$
Number of skids (99)	$+1$	PC
Assembly process efficiency (5)	-1	Mean cycle time

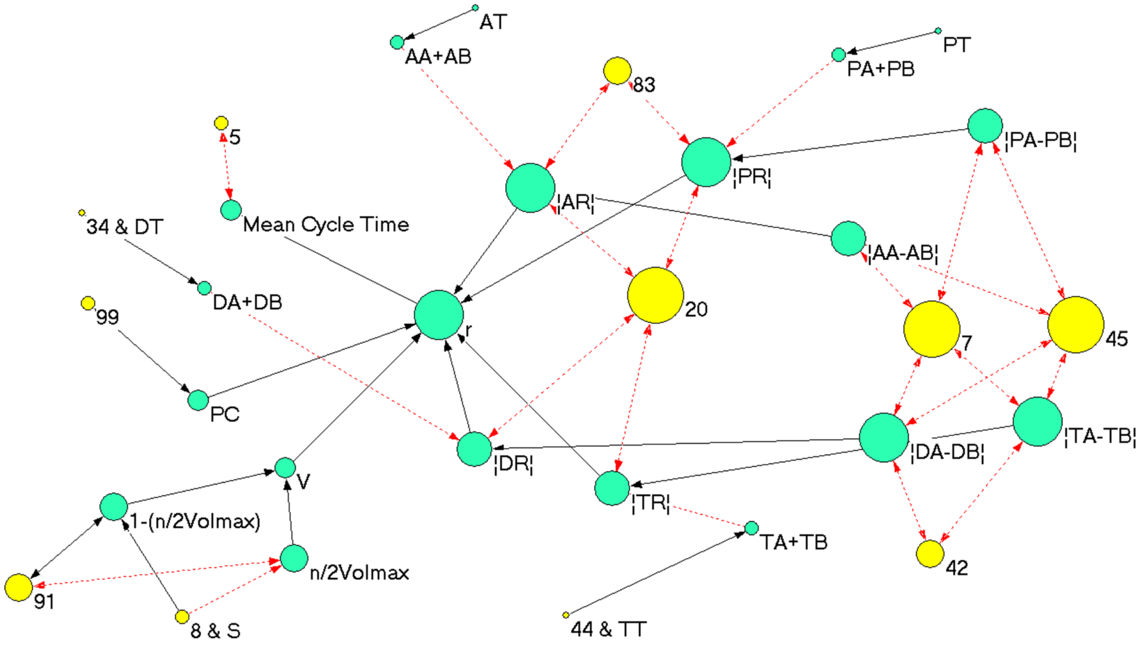


Fig. 11 FCM plot of the observation operational model with linked and merged concepts from the collective interview

$(A_{\text{interviews(all)}})$ from Table 3 are shown in yellow (light shading). The relation between the 23 observation concept codes and 11 collective interview concept codes in Table 3 highlight that the observation data are focused on physical entities and actions within the system that are directly observable from an observation perspective, which makes sense because the assembly process was directly observed in this case. In addition, 8 of the collective interview concepts relate to 20 observation concepts, showing how the observation accounts for very detailed information related to physical entities. The numerous interview codes is contributable to the breadth of information collected from interviews that often cannot be directly observed at the assembly process, or would require multiple and broader system observation points.

As Fig. 11 shows, of the 23 codes in the observation dataset, there were only 3 codes that were identical to codes in the collective interview dataset. There were an additional 12 codes in the observation dataset that were linked to the collective interview dataset. There were 8 codes that were unique to the observation dataset. Of the 123 codes in the collective interview dataset, 105 were unique. It is important to note that different data collection methods collect different information and that the observation here is focused on a quantitative model while the interviews are focused on qualitative information. A significant value of the proposed modeling approach is that it integrates qualitative and quantitative data from the two methods, which contribute uniquely to the system model and relate to one another. The fully integrated observation and interview adjacency matrix $(A_{\text{interview(all)\&observation}})$ is plotted in Fig. 12. All the collective interview adjacency matrix $(A_{\text{interview(all)}})$ concepts are shown in yellow (light shading). All the concepts form the observation adjacency matrix $(A_{\text{observation}})$ are shown in aqua (dark shading).

Figure 12 illustrates quite clearly that the interview data contributes a breadth of concepts to the integrated model, while the observation data contribute to a narrower scope of concepts. The integrated model's ability to show both is a significant strength of the FCM modeling approach taken in this paper. In Fig. 12, the size of the nodes indicates the most central concepts (highest centrality value) in the integrated adjacency matrix. In order of centrality value, these are: being able to position materials for the assembly process (code 7); permanency of workforce (builders) (code 17); having a designated position for materials around the table (code 45); builders dividing work evenly (code 20); and idealness of assembly process (code 16). Determining what are the most critical concepts integral to the re-design task, and classifying these variables, is the purpose of the analysis (Sect. 5).

5 Analysis for variable classification

Using Eqs. 1–3, the concepts (codes or nodes) represented in each FCM plot are classified as receiver (overall effect concept), transmitter (overall cause concept), or ordinary (overall central concept) variables. This analysis is organized and highlighted per six categories:

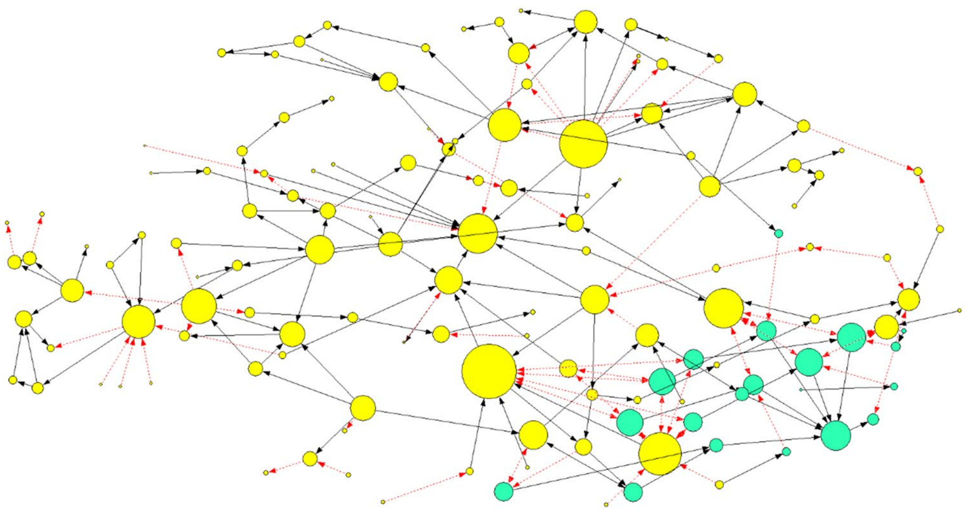


Fig. 12 FCM plot of the integrated observation and interview adjacency matrix

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

In the case of a tie within a category, all the tied codes within 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 +. The collective interview analysis is presented in Table 4; the observation analysis is presented in Table 5; the integrated collective interview with observation analysis is presented in Table 6.

Note: in the case of the observation adjacency matrix and plot analyzed in Table 5, 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.

The analysis in Tables 4, 5, and 6 shows that the fuzzy cognitive models for the collective interview and observation highlight different overall causes, effects, and central concepts. By synthesizing the two together, the integrated model finds additional considerations. Code 7 arises with a high out-degree, in-degree, and centrality and as a top 3 overall central concept. Code 20 and 45 also arise as top 3

Table 4 Code classification for the collective interview FCM

Code	Code description	Out-degree $od(v_j)$	In-degree $id(v_j)$	Centrality $c(v_j)$
17	Permanency of workforce (builders) +	**12C**	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 +	**5C**	0	5
92	Current location of the assembly area (versus past location) +	**5C**	0	5
16	Idealness of assembly process +	0	**9.5E**	9.5
5	Assembly process efficiency +	0	**4E**	4
96	Lead hand availability/utilization +	0	**5E**	5
40	Ease of flow of materials *	1.5	6	**7.5N**
51	Material handlers pick up finished pallet +	2	7	**9N**
27	Assembly components missing *	4	4	**8N**

Table 5 Code classification for the observation FCM

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

overall central concepts. The overall cause, effect, and central concepts in the fuzzy cognitive models (Tables 4, 5, 6) are interpreted in terms of a general engineering system design model in the following discussion.

6 Discussion

Creating a system model of an engineering design for system analysis requires an understanding of what is being modeled (meta-cognition) to relate the specific model (the FCM models) to the general model. The engineering system design model, and its variations in four regional schools, is integrated into a 'unified' model by Lin and Zhang (2004) and Zhang et al.'s (2011). In the following paraphrased summary of their model, the elements of their model are related to the variable classifications in the fuzzy cognitive model (*in italics*). In Lin and Zhang(2004) and Zhang et al. (2011) model, the context is the boundary between the system and the environment. In this case, since users are integral to the operation of the socio-technical system and are thus a part of the system model, they are inside the system boundary.

Lin and Zhang(2004) and Zhang et al. (2011) model of the design system consists of physical entities that are meaningfully connected and directly related to the fuzzy cognitive mapping model analysis overall cause, effect, and central concepts from Sect. 5 as follows. When the system is in operation, these entities are perceived as states that reflect the system structure (*FCM analysis overall central concepts*). Internal constraints relate to the connection between entities that form the system at time t (*FCM analysis overall central concepts*); the external constraints are imposed from the environment to the entities in the system (*FCM analysis overall cause concepts*). Information, energy, and materials

Table 6 Code classification for the integrated collective interview with observation FCM

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	**14N**
17	Permanency of workforce (builders) +	**12C**	0	12
43	Like an assembly line +	6	1	7
68	Size of customer account +	**5C**	0	5
92	Current location of the assembly area (versus past location) +	**5C**	0	5
16	Idealness of assembly process +	0	**9.5E**	9.5
51	Material handlers pick up finished pallet +	2	7	9
5	Assembly process efficiency +	0	**4E**	4
96	Lead hand availability/utilization +	0	**5E**	5
20	Builders dividing work evenly *	5	5	**10N**
45	Having a designated position for materials around the table *	5	6	**11N**

are transmitted from the outside environment into the system as independent state variables, or inputs (*FCM analysis overall cause concepts*). Information, energy, and materials are transmitted from the system to the outside environment as dependent state variables, or outputs (*FCM analysis overall effect concepts*). The system behaves according to how the inputs relate through the entities into outputs; principles govern this behavior (*a principle is a FCM analysis overall cause concept*). The function of the system relates the behavior to the context (*a function could be measured as an outcome or FCM analysis overall effect concept*).

The relation between Lin and Zhang(2004) and Zhang et al. (2011) design system model and the fuzzy cognitive model is illustrated in Fig. 13. In Fig. 13, the box represents the system with a context boundary and internal structure. Cause concepts are shown as gray ellipses; effect concepts are shown as black ellipses; white ellipses and text are shown as central concepts. As stated earlier, a 'cause' is defined 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.

Based on this analogous relationship between the general system design model and the FCM models, the FCM variable classifications from Tables 4, 5, and 6 (overall cause, effect, and central concepts) are related the standard terminology for the engineering system design model.

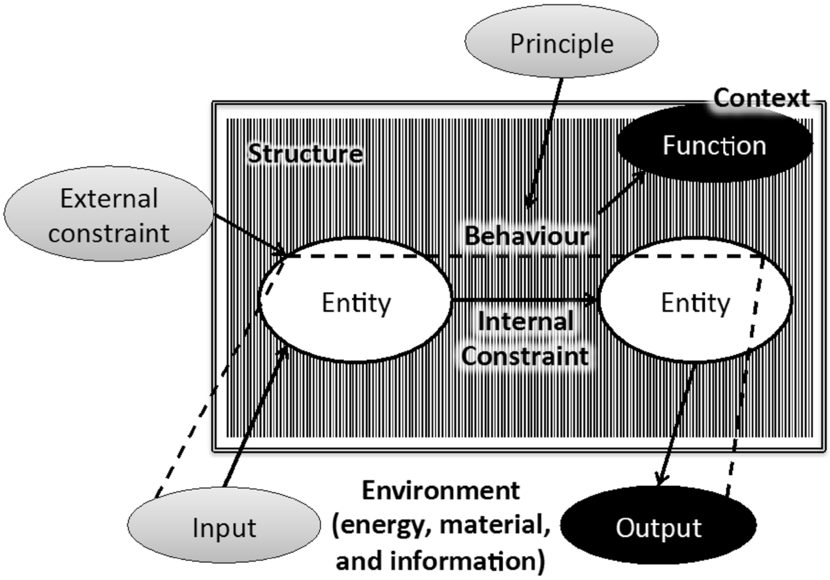


Fig. 13 Interpreting the general system design model into cause, effect, and central concepts

- Inputs: inputs appear in the FCM model as overall causes that move from the outside environment to affect entities in the system.
- External and boundary constraints: external and boundary constraints appear in the FCM model as overall causes that move from the system boundary to affect entities in the system.
- Design principles: design principles appear in the FCM model as overall causes that move from outside or within the system boundary to affect the behavior of the system.
- Outcomes and outputs: outcomes and outputs appear in the FCM model as overall effects that move from entities within the system to the outside environment.
- Functions: functions appear in the FCM model as overall effects that move from the behavior in the system to relate to the context.
- Operations and structure: operations (events) and structure (organization) appear in the FCM model as central concepts that exist within the system boundary.

Relating the FCM variable classifications to the engineering system design model standard terminology is made even more useful to designers by synthesizing this insight into re-design foci. These re-design foci are themes related to the FCM variables (overall causes, effects, and central concepts), determined by first grouping the structure aspects—process, layout, and training in this case. Process and layout are common re-design foci for manufacturing systems that are informed and specified by the FCM analysis variable classification per the case study. The other identified elements of the system (operations, function, outputs, outcomes, design principles, external and boundary constraints and inputs) are then integrated into these re-design foci and where they are not clearly in alignment warrant new re-design foci (in this case differentiated design was a new insight, so it warranted emphasizing in the re-design foci). Throughout this merging and comparison process attention is paid to ensure that the participant meaning of the codes is preserved. In doing so, the analysis of the behavior and use of the existing design solution (system model) is harnessed to inform the re-design process. The result of this FCM variable classification into standard system model terminology and re-design foci is outlined in Table 7.

The classifications of the variables in Table 7 are further outlined relative to their standard system model terminology and re-design foci as follows.

6.1 FCM overall cause concepts: system inputs, constraints, and design principles

The inputs are most readily identifiable from the observation FCM model (Table 5). The inputs identify what should be monitored in the re-design because changes in them will have a significant impact on the system. In subsequent re-design phases of the case study, these inputs remained the same and the participant users and designers designed with these specifications in mind (e.g., the overall assembly product designs were specified to the production environment). Note: the number of picking (PT) and assembling tasks (AT) represent materials since the number of tasks are determined by the packaging of the components, which is performed in a system external to the immediate one being studied.

The external and boundary constraints are most readily identifiable from the interview and integrated FCM models (Tables 4 and 6). The external and boundary constraints represent constraints in the re-design that a designer must bear in mind. In subsequent phases of the case study, the participant users and designers designed within these limitations (e.g., the re-design had to optimize space within the space that was currently designated for the assembly process). The permanency of the workforce and size of the customer account are determined outside of the immediate system in the broader business context; the current location of the assembly area is a space constraint defined at the current system boundary.

The FCM model analyses in Tables 4 and 6 included the concept "like an assembly line," which was driven by the overall cause concept "applies to us" as a design principle. Upon further inspection of this node, the participants cite that this principle will affect the amount of work for builders, lead hands, and material handling; the ease of flow of materials; a new machine; and the ease of assembly work (the entitles in the system and their internal constraints). In other words, the intent of the re-design principle "like an assembly line" is not simply to 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 task and design thinking—a shift in intention from a universal to a differentiated solution that "applies to us" ("us" being the design users). The FCM model analysis in Table 5 also includes overall causes being the difference in the total and different components between builders A and B as well as the difference in picking and assembling tasks between builders A and B. These concepts are driven by the design principle of "difference"—in other words, how division of labor is interpreted and applied. The design principles are identified in all the FCM models (Tables 4, 5, 6). The design principles are critical to re-design because they represent organizational principles of the system; these are significant insights to consider in the conceptual phases of the re-design.

6.2 FCM overall effect concepts: system outputs, outcomes, and function

In the FCM model analyses (Tables 4, 6), "idealness of the assembly process" is viewed as an overall outcome. Upon

Table 7 Classifying FCM variables into standard system model terminology and re-design foci

FCM variables: Overall causes, effects, and central concepts (from Tables 4, 5, and 6)	Standard system model terminology	Re-design foci			
		Process	Layout	Training	Differentiated design
Start of production run (information or signal)	Input	X			
Number of total components (TT) and number of different components (DT) in the final product assembly (materials)	Input	X	X		
Pallet count, which is determined by the size of the platform component (material)	Input		X		
Number of picking (PT) and assembling tasks (AT) for the final product assembly	Input	X	X		
Permanency of the workforce (builders)	Constraint			X	
Size of customer account	Constraint	X	X		
Current location of the assembly area	Constraint		X		
"Like an assembly line" driven by the overall cause concept "applies to us"	Design principle	X	X	X	X
Difference $\lvert TA-TB\rvert$, $\lvert DA-DB\rvert$, $\lvert PA-PB\rvert$, $\lvert AA-AB\rvert$	Design principle	X	X	X	X
Idealness of assembly process	Outcome	X			
Lead hand availability/utilization	Outcome	X			
Mean cycle time value	Function	X			
Assembly process efficiency	Function	X			
Material handlers pick up finished pallet	Operation	X	X		
Distribution of work related to the total number of components, different components, picking and assembling tasks (which are integrated into the observation complexity ratio)	Operation	X	X		
Builders dividing work evenly	Operation	X	X		
Assembly components missing	Operation	X	X	X	
Having a designated position for materials around the table	Structure		X		
Being able to position materials for the assembly process	Structure		X		
Ease of flow of materials	Structure		X		
Production phase variable, which accounts for faster cycle times at the end versus beginning of a production run; this trend is characteristic of learning curves	Structure			X	

closer inspection of the cause and effect chain, this "idealness" is achieved 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 and permanency of the workforce) and leads to assemble final assemblies without any components missing (the output). Lead hand availability/utilization is also identified as an overall outcome. The outcomes and outputs are identified in the interview and integrated FCM models (Tables 4, 6). The outcomes and outputs identify what should be monitored in the re-design because changes in them will have a significant impact on the value of the system and its impact on the broader system. In subsequent re-design phases of the case study, these participant users and designers designed with these outcomes and outputs in mind (e.g., one of the re-designs was a "double-check system" to ensure that final assemblies had no components missing (the output)).

In the FCM model analyses (Tables 4, 5, 6), the mean cycle time value and assembly process efficiency are measurements of the overall function. In this system model of an assembly production system, the function is to transform inputs into outputs; cycle time and efficiency measure this rate of transformation. The function is measured in the interview and integrated FCM models more generally as efficiency (Tables 4, 6) and more specifically as cycle time in the observation FCM model (Table 5). The function identifies how the impact of the re-design can be measured. In the case study, the before and after conditions of the system were compared with respect to the cycle time to quantify the system function improvement.

6.3 FCM central concepts: system operations and structure

The operation and structure are identified in all the FCM models (Tables 4, 5, 6). Not all these operations and structure are desirable, and so this analysis highlights areas where the re-design can target corrective actions with improved operations and structure. The operations and structure identify specifics about what should be re-designed in the system, which are synthesized together and with the previous system elements identified into re-design foci and tasks as follows.

6.4 Re-design foci and tasks

Re-design foci and task #1: Process 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, utilization of workers including lead hands, etc.). Together, this behavior 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 tasks #1 and #2 synergistically.

Re-design foci and task #2: Layout Existing space (current location of the assembly area) 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 is challenging to have designated positions for materials due to the variety of assembly components and final product assemblies and the distribution of the components and picking and assembling tasks. The layout must accommodate pallet positioning and removal.

Re-design foci and task #3: Training The temporary 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).

Re-design foci and task #4: Differentiated design To accomplish re-design tasks #1–3, the re-design process is intent on working with users to ensure that the re-designed assembly production system "applies to us" (differentiated design) and accommodates differences. This user-oriented re-design process begins with these four re-design tasks, which inform the social contract between the designer and users to resolve the tasks together. In doing so, the re-design process is also committed to the continued work culture, described by one participant as "chivalry."

6.5 Participants' re-designs

In the case study, the re-design foci and tasks were used to plan for and conduct subsequent participatory design events where users were invited to take part in developing concept and detail re-designs through reflection-in-action. The first two events focused on process and layout and the third event focused on training; differentiated design was a theme throughout. The participants' re-designs (Table 8) are shown here to illustrate their alignment with the four re-design foci and tasks. The re-designs are discussed in relation to the assembly components and products (Table 9).

These re-designs were implemented and then tested with users, specifically using the operational model presented here to compare the before and after system models to assess the impact of the re-design implementation. The function of the system improved—the mean cycle time was found to be lower after the re-design versus before with a statistically significant mean difference of − 0.72 min/assembly (Townsend and Urbanic 2015). For further details on the re-designs and their impact, please see Townsend (2015).

Table 8 Participants' re-designs following participatory design events (aligned with re-design foci)

		Before	After re-design
Re-design foci and tasks	#1 Process	• Two builders both picked (selected) components and assembled (combined and positioned) selected components • Aimed to divide components evenly but was challenging in practice	• Two new builder roles (picker and assembler)—share components and divide work based on roles (per Table 10) • Job rotation at each break (avoid physical and mental tiredness) • Picker and assembler also have shared responsibilities. After performing the process a few times, the picker and assembler decide who is able to do the following shared tasks 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 the forklift driver for more skids of component B and component C; and if the final assembly is heavy, both builders put final assembly on skid
	#2 Layout	• No designated positions for materials • Limited forklift access • Quality checked at end of shift or production run by material counts	• Materials are organized with designated positions in line with the new picker and assembler roles per Fig. 14 • Table is rotated 90° to improve material flow (clear forklift access for pallets) • New quality double-check tool (grid and labeling system) involves both builders and provides an opportunity to double-check component quantities, avoiding miscounts
	#3 Training	• No organized training (often ad hoc, builders training builders after errors occurred)	• New training checklist (reviewed with new builders by a specified trainer) identifies important information including five sections: (1) The paperwork: how do I read and fill out the work order? (2) The UPC: how do I know what this product is? (3) The process and layout: what do I do? (4) Demonstration by the trainer: how does all of this work? (5) Questions?
	#4 Differentiated design	• Participants expressed in the interviews a desire to have a re-design that "applies to us"	• Differentiated design was achieved with all re-design foci/tasks—achieving a customized solution that works for the users. • Process: participants designed the shared tasks to be discussed between the two builders because 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. Not all builders work at the same pace for a variety of reasons (e.g., work ethic, interest, motivation, skill, etc.). Shared tasks create flexibility to adjust to these different builder conditions • Layout: new layout is a combination of a product-process (cellular) layout and a fixed product layout; process is defined from the new builder roles versus roles of a machine (the latter typical for cellular layouts) • Training: participants emphasized the demonstration aspect of the training, so builders can ask the trainer questions. New builders may have different questions based on their past experience, previous training, skills, knowledge, etc. This is responsive to builder needs, promoting dialogue between builders and the trainer. The format also addresses different learning styles (discussion, reading, demonstration, and visual)

Table 9 Final assembly component variants and precedence (from pre- and post-observation)

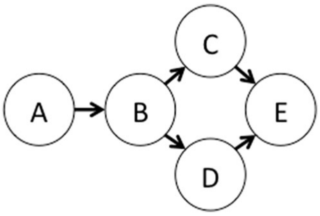
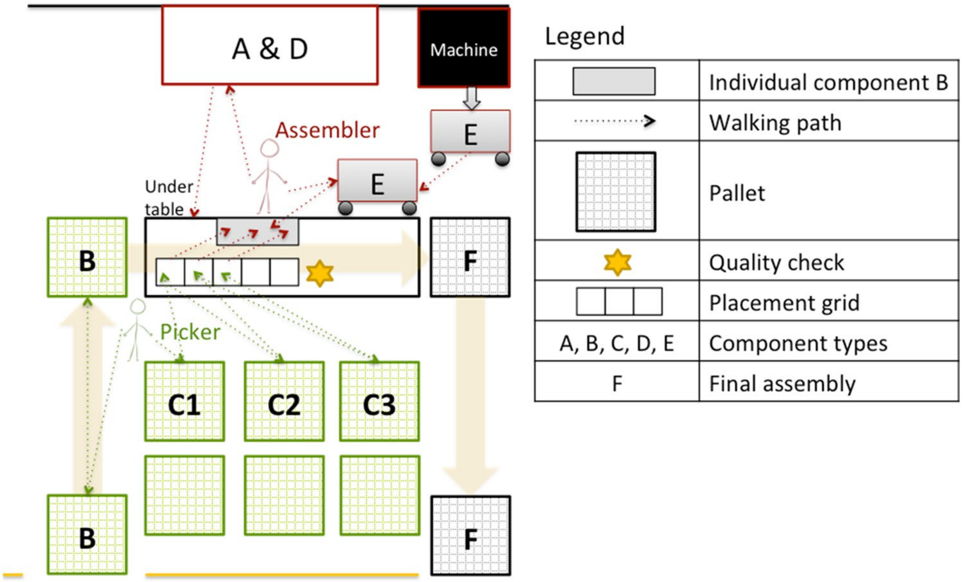
Precedence graph of the component order of assembly	Assembly variant combination descriptions	Component type A	B	C	D	E
	# of sub-types	4	5	37	4	1
	Min # different sub-types	0	1	1	0	1
	Max # different sub-types	1	1	8	1	1
	Min # of components	0	1	24	0	2
	Max # of components	1	1	60	2	15
	Flexible (FL) or rigid (RD)	FL	FL	RD	FL	FL

Table 10 Task division for the new picker and assembler builder roles

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 B • 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

Fig. 14 The re-designed layout



6.6 Trustworthiness and validation of the proposed approach

It is critical to note the epistemological orientation of the qualitative research approach taken herein with respect to the interviews, which considers that participants reveal knowledge to the researcher who in turn strives to see if s/he can see what the participants see, to then help others to see it. This contrasts the positivist epistemological position often taken in engineering, taken herein with respect to the observations, which aims for objectivity. The proposed approach integrates both research orientations because when re-designing a socio-technical system it is critical to see the system as the users see it because ultimately their view of the system *and* the system itself need to be transformed. Krefting (1991) and Shenton (2004) present a framework that aligns qualitative trustworthiness and quantitative validation; the following provides evidence of the establishment of truth value, consistency, applicability, and neutrality in the research presented.

Krefting (1991) and Shenton (2004) establish truth value as the confidence in the findings and context in which the study was undertaken (credibility and internal validity) as well as consistency as the ability to generate the same findings if the inquiry was replicated (dependability and reliability). In the proposed approach, a detailed methodology and case study context was presented. Eight interviews were conducted with participants from five different roles. The observation random sampling consisted of 226 samples, collected over several months. Integrating both methods provided both breadth and depth of information. Reliability in the coding here was established using multiple data collection methods (interview and observation), keeping a code book during the coding process for consistency, and through the coding redundancy and merging. 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. One person coded and five academics with PhDs and several interested participants reviewed the models and analysis. The system model was analyzed in terms of overall variable classifications, which informed the re-design task with ongoing member checking in the next phases of the larger study [further information in Townsend (2015)]. By utilizing research ethics protocols, the researchers/designers established trust with the user participants, which was critical to establishing data reliability in both the interview and observation data collection methods.

Krefting (1991) and Shenton (2004) establish applicability as the degree to which the findings can be applied to other contexts (transferability and external validity). The methodology provides background data on the industrial context with detailed methodology; further information can be found in Townsend (2015), which enables context comparison. Assumptions of the proposed modeling approach include the availability of participants; that the process is observable; the process transforms inputs into outputs; the 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; and there is time to perform the interviews, observations, coding and analysis. To fully understand the transferability of the re-design approach developed here to other contexts, it needs to be tested with other types of socio-technical systems.

Krefting (1991) and Shenton (2004) establish neutrality as the freedom from bias (confirmability and objectivity). The proposed methodology is detailed and demonstrated with clear examples. A substantial amount of evidence is analyzed with this detailed methodology.

6.7 Limitations and future research for the proposed approach

The limitations of the proposed approach for FCM with users include the following. First, in an industrial, non-research application of the proposed approach the designers will need to consider how trust between the designers and users will be established outside of research ethics protocols.

Next, developing questions for the interviews requires consideration. For the interviews, it was critical to ask questions that were broad enough to allow for openness yet within an appropriate scope to manage the number of codes. In future applications of the proposed approach, designers will need to carefully select questions adapting the ones established here.

In addition, it is critical to address model reliability and validation with the time required to conduct the FCM approach. For the observations, random sampling across several months promoted data reliability but required significant time. This time enables the designer to understand the data and design context more thoroughly, which benefits data analysis and interpretation, but there is a time and quality trade-off. Similarly, the coding itself takes time and the designers will need to determine an appropriate degree of detail.

Finally, it is critical to note that the fuzzy cognitive modeling approach presented here was conducted in one design context. Future research will need to test this approach in other applications and design contexts to test its transferability, adaptation requirements, and limitations. Future applications to test the proposed approach in engineering design could consider its usefulness in assessing use in product design as well as interactive design between multiple users and technology (e.g., user platforms, collaborative robots, user involvement in industry 4.0, etc.). The latter trends in engineering design emphasize growing inter-dependencies between users and technology, where user insight will increasingly be needed by engineering designers to create robust and sustainable designs.

6.8 Contributions and benefits of the proposed approach

This proposed approach provides an opportunity for users to directly participate in system analysis and modeling when re-designing a socio-technical system. A broad spectrum of users are invited to participate in interview and observation to develop a system model that integrates users' collective knowledge and identifies synergistic re-design foci, as described in this work. Benefits of the proposed approach include the following. Few modeling methods integrate qualitative and quantitative information, which lend unique insights. The proposed approach also balances social and technical aspects, which is needed for modeling a socio-technical system comprehensively. In the approach, users define the system model relative to their collective experience in their own words (interview) and actions (observation). In this regard, modeling is performed relative to the user experience versus the user experience being suited to the modeling method. This may seem subtle but it is important to the users to be heard and to the ability of the model to reflect reality. Suiting the modeling to the user experience enables users to share information freely and designers to see (observe) and listen (interview); it enables users to guide the level of detail that is relevant; it means that what is important has not already been determined by the modeling method and, in turn, provides an opportunity for unexpected insights (e.g., how would the user idea of "differentiated design" fit in with another method?). Further studies can directly compare the proposed method with other system modeling techniques (e.g., simulation, system dynamics, etc.) to identify additional benefits and limitations.

7 Conclusion

This research outlines the following approach for building a socio-technical system model with users for system analysis in engineering design. The proposed fuzzy cognitive approach for system modeling engages users as participants (18 here) in holistically modeling the system design; here, an assembly production system (a socio-technical system archetype) was modeled. Data on the participants' use of the existing system are collected in situ via interview and observation. The observation sets are synthesized with statistical analyses into an operational model. With fuzzy cognitive mapping techniques, the interview data and operational model are coded into cause, linkage, and effect relationships. The coding is arranged into an adjacency matrix and then plotted as a di-graph where cause and effect concepts are nodes and the linkages are vectors. Each interview is coded individually then merged to form a collective interview adjacency matrix and FCM model. The collective interview adjacency matrix and FCM model is then synthesized with the observation operational adjacency matrix and FCM model into an integrated FCM model. A significant value of the proposed modeling approach is that it integrates qualitative and quantitative data from interview and observation, which contribute uniquely to the system model and relate to one another. With FCM analysis techniques, the models are analyzed for overall cause, effect, and central concepts.

This system model benefits the design process by directly integrating the multiple perspectives of design users into one system design model, which enables designers to zoom in to see the detail and zoom out to see a holistic perspective. Through the FCM analysis, the design system elements of the existing socio-technical system design solution are made explicit, including inputs, external and boundary constraints, design principles, outcomes and outputs, function, and operations and structure. This is particularly useful in re-design, as is demonstrated in the industrial re-design project here, where the FCM analyses are synthesized into re-design foci and tasks that inform re-design.

The limitations of this approach include the importance of trust between the designer(s) and users and the time required to conduct interviews, observations, and the FCM process. Future research needs to test this approach in additional socio-technical system types and design contexts, and in direct comparison to other modeling methods, to characterize its transferability and further define its benefits and limitations.

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Appendix A: Transcript excerpt and FCM coding

Interviewer: How would you describe the current assembly process?

Participant: Umm… simplified.

Interviewer: Ok

Participant: You know, we've, over the years we've gone from doing a few hundred now to probably [XX] …so, and, um, we're currently struggling with space and personnel. So we've, it's grown into its own type of

Table 11 Interview excerpt sample coding

Verbatim cause concept in the interview transcript	Overall code	Link	Overall code	Verbatim effect concept in the interview transcript
Over the years we've gone from doing a few hundred orders now to probably [XX]	1	−1	2	Space
Over the years we've gone from doing a few hundred orders now to probably [XX]	1	−1	3	Personnel
The assembly process has grown into its own type of department within a department	4	−1	3	Staff the assembly process accordingly
The assembly process has grown into its own type of department within a department	4	−1	5	Be efficient at the assembly process
Now that we don't have a lot of room in our building	(−2)	−1	6	Bring all of the pieces for all of the assemblies in a given production run down to the production floor
Now that we don't have a lot of room in our building	(−2)	−1	7	Lay out all of the pieces for all of the assemblies in a given production run on the production floor
Bring all of the pieces for all of the assemblies in a given production run down to the production floor	6	+1	8	Starting the production run
Lay out all of the pieces for all of the assemblies in a given production run on the production floor	7	+1	8	Starting the production run
Bring all of the pieces for all of the assemblies in a given production run down to the production floor	6	+1	9	Check over all of the pieces for all of the assemblies in a given production run
Check over all of the pieces for all of the assemblies in a given production run	9	+1	10	Sign off on checking over all of the pieces for all of the assemblies in a given production run
Sign off on checking over all of the pieces for all of the assemblies in a given production run	10	+1	11	Say ok let's build the assembly
Say ok let's build the assembly	11	+1	5	Efficient way to build the assembly
Say ok let's build the assembly	11	+1	12	Make sure all of the pieces for all of the assemblies in a given production run are accurate
Lack of space	(−2)	+1	(−6)	Material handlers gathering the assembly pieces at multiple times
Lack of space	(−2)	−1	6	Material handlers gathering all of the assembly pieces at once

department within a department now and we're struggling to staff it accordingly and be efficient at it. Now that we don't have a lot of room in our building we're unable to bring everything down and lay it all out ahead of the run. Usually what you'd like to do is bring everything down, let's say you are going to do 200 [assemblies], you want to bring every piece of that [assembly]…all the [X], all the [Y], all the componentry, bring it down, make sure it's all accurate, check it over, sign off on it, and then say "ok… let's build." That's the efficient way. Now, we currently have to bring it in pieces, so at multiple times our material handlers are going to gather the pieces rather than doing it once due to our lack of space…. [interview continues]

See Table 11.

Appendix B: Integrated interview plots (interviews 1, 2 and 3)

See Figs. 15 and 16.

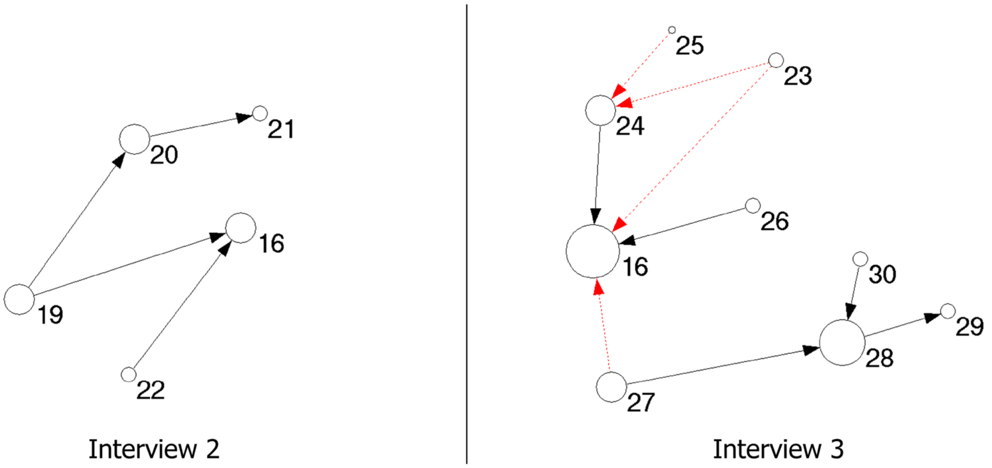
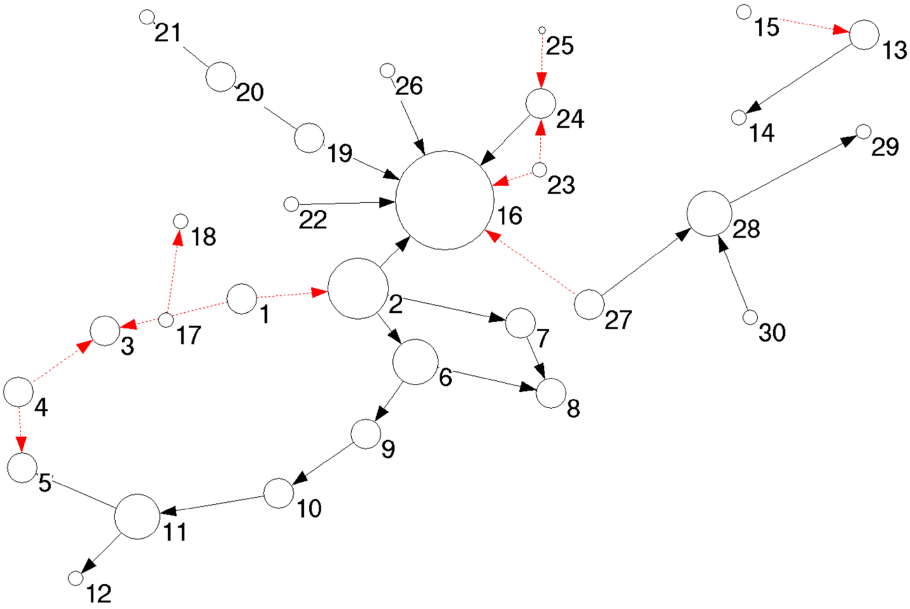


Fig. 15 FCM plot for interviews 2 and 3

Fig. 16 FCM plot for integrated interviews 1, 2, and 3



Appendix C: Codes from participant interviews

See Table 12.

Table 12 Interview codes

Overall code	Code meaning	Overall code	Code meaning
1	Order growth	61	Lead hand responsibility for make sure assemblies are built and according to priorities
2	Sufficiency of the current amount of space	62	Communication with sales team and commitment for order
3	Staffing the assembly process accordingly (enough staff)	63	Forecast accuracy
4	Assembly process grown into its own type of department	64	Order accuracy (purchase order matches forecast)
5	Assembly process efficiency	65	Account dependability
6	Bring all materials for an order at once to the assembly line	66	Right amount of assemblies built
7	Being able to position materials for the assembly process	67	Assemblies disassembled
8	Start production—“ok let’s build”	68	Size of customer account
9	Check over all assembly components in a given production run	69	Accuracy of MRP (material) system
10	Sign off on checking over all the assembly components in a given production run	70	Accuracy of component quantity
11	Say ok let’s build the assembly	71	Accuracy of supplier components quantity
12	Make sure all the pieces for all of the assemblies in a given production run are accurate	72	Special order request
13	Designated responsibility for managing the assembly process	73	Additional manufacturing cost
14	Assembly process getting attention it deserves	74	Component held off-site
15	Assembly building and procurement added to a very busy staff	75	Request component from supplier
16	Idealness of assembly process	76	JIT delivery of component
17	Permanency of workforce (builders)	77	Quality of relationship with supplier
18	Assembly builder changeover	78	Amount of corrugate stored in the warehouse
19	Having another builder to work with	79	Room in the warehouse
20	Builders dividing work evenly	80	Utilization of builders
21	Ease of builder work	81	Builders talking to other builders
22	Builders make decisions about work	82	Well-defined roles for builders
23	New machine	83	Coordinated actions between builders
24	The way the assembly process is currently done	84	No formal builder training
25	Additional help for builders	85	Builders training builders
26	Chivalry inside the building	86	Lead hands training builders
27	Assembly components missing	87	Time between pre-order and actual order
28	Builders re-check assemblies looking for mistake and correcting it	88	Variation in customer needs
29	A lot of work for builders (time consuming)	89	New business opportunity
30	Material handlers bring wrong skid of materials	90	Scrambling
31	Amount of time training builders	91	Order size
32	Amount of work for lead hands	92	Current location of the assembly area (versus past location)
33	Builders knowing what to do	93	New space for assembly area
34	Variety of components	94	Ability to see builders
35	Lead hands check/count assembly components	95	Ease of lead hand and builder communication
36	Lead hand knows where mistake is	96	Lead hand availability/utilization
37	Lead hands communicate with builders regarding mistake	97	Structural constraints (walls, racks, desk, etc.)
38	Builder opens up every assembly	98	Safety wise, probability of accident

Table 12 (continued)

Overall code	Code meaning	Overall code	Code meaning
39	Builders check every assembly component	99	Number of skids
40	Ease of flow of materials	100	Building assembly platform
41	Material handler and lead hand training on setting up and staging materials	101	Number of assembly processes going on at the same time
42	Even out the number of products on each side of the table	102	Emptiness of aisle
43	Like an assembly line	103	Access final pallet in warehouse location
44	Total number of components	104	Temporary warehouse location
45	Having a designated position for materials around the table	105	Amount of time for material handlers
46	Small work area	106	Lead hands receive emails of changing priorities
47	Maneuver skids	107	Lead hand checks on builders
48	Variety of assemblies	108	Builders want to do a good job
49	Assemblies are complete	109	Nervous
50	Builders pull out finished pallets and stage on floor	110	Terrified
51	Material handlers pick up finished pallet	111	Day easier
52	Immediately wrap pallet	112	Away from forklifts
53	Weight pallet	113	Self-sufficiency of builders to move products
54	Put pallet up in warehouse	114	Using hand jacks
55	Finished pallet backlogs	115	Applies to us
56	One material handler designated for [assemblies]	116	Having technology knowledge and awareness
57	Material handler responsible for pulling assemblies (bringing new components to the assembly area)	117	Interest in technology
58	Material handler responsible for putting away finished assemblies in the warehouse	118	Updated way to build things
59	Material handler responsible for pulling orders from the warehouse to ship	119	Working smarter not harder
60	Material handler responsible for shipping out assemblies	120	Builders follow instructions

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