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Design for human factors (DfHF): a grounded theory for integrating human factors into production design processes

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The 'design for human factors' grounded theory explains 'how' human factors (HF) went from a reactive, after-injury programme in safety, to being proactively integrated into each step of the production design process. In this longitudinal case study collaboration with engineers and HF Specialists in a large electronics manufacturer, qualitative data (e.g. meetings, interviews, observations and reflections) were analysed using a grounded theory methodology. The central tenet in the theory is that when HF Specialists acclimated to the engineering process, language and tools, and strategically aligned HF to the design and business goals of the organisation, HF became a means to improve business performance. This led to engineers 'pulling' HF Specialists onto their team. HF targets were adopted into engineering tools to communicate HF concerns quantitatively, drive continuous improvement, visibly demonstrate change and lead to benchmarking. Senior management held engineers accountable for HF as a key performance indicator, thus integrating HF into the production design process.

Practitioner Summary: Research and practice lack explanations about how HF can be integrated early in design of production systems. This three-year case study and the theory derived demonstrate how ergonomists changed their focus to align with design and business goals to integrate HF into the design process.

Keywords: theory; human factors; design; manufacturing; macro ergonomics

1. Introduction and goal of paper

1.1 Human factors can improve the 'human' aspects of operational performance

Human factors (HF: used synonymously with ergonomics) is the scientific discipline concerned with the understanding of interactions among humans and other elements of a system to optimise human well-being, and overall system performance (abridged from International Ergonomics Association 2013). The application of HF has been shown in numerous studies to not only improve workers' well-being (such as reducing injuries and absenteeism, and increasing job satisfaction), but also to increase productivity, improve customer service and reduce human error (Eklund 1995; Abrahamsson 2000; Drury 2000; Goggins, Spielholz, and Nothstein 2008; Neumann and Dul 2010). Studies have reported on HF aspects related to production design elements (Neumann et al. 2006), the effect of lean on both work environment and employee health and well-being (Hasle et al. 2012), sociotechnical systems and organisational design (Dabhilkar and Åhlström 2013), and worker job stress (Conti et al. 2006). Studies have also pointed out that quality and HF are well-matched processes and complementary, and together achieve levels of performance they cannot attain separately (Drury 2000; Erdinc and Yeow 2011). Production engineers and operations managers need to meet the ever-changing demands for production, quality and service delivery through the combination of workers and machinery – and HF can assist with the worker interface (Drury 2000). Investigations in the Canadian context, however, indicate that human factors are largely recognised as an occupational health and safety (OH&S) function, with limited uptake and application towards productivity and quality goals (Theberge and Neumann 2013). This study addresses the issue of the uptake of HF by engineers in the production design process to help deliver improved operational performance.

1.2 Human factors should be integrated earlier in production design

Instead of applying HF after design problems have manifested in injuries or concerns (i.e. an OH&S function), it has been argued that HF should be integrated as early as possible in the design processes (Jensen 2002; Seim, Broberg, and Andersen 2012; Neumann and Village 2012). The cost is lowest and the availability of solutions is highest in the early stages of design (Miles and Swift 1998). Hendrick (2008) reported that the earlier HF is applied in design, the cheaper the cost and the

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greater the benefit. On large system development projects, effective HF programmes constituted only 1% of the engineering design budget (Hendrick 2008). With a few exceptions, engineering design has not taken advantage of HF to improve design of work systems in any widespread fashion.

Researchers have argued that HF aspects of design are not widely covered in the education and training of engineering and management disciplines (Neumann and Dul 2010). Boudreau et al. (2003) effectively point out the differing assumptions and treatment of 'human' aspects of production between operations management (OM; largely derived from industrial engineering) and human resources management (HRM; from psychology and sociology). The authors suggest bridging the OM and HRM gap. We suggest, as do Neumann and Dul (2010), that HF aspects of design of an assembly production, such as ease and complexity of assembly and worker fatigue and performance, are integral to both operations management and human resources management. This research helps to fill the gap by identifying how HF can be moved from a limited health and safety focus and integrated more fully into both OM and HRM as they contribute to production systems design.

1.3 The scientific literature lacks theory guiding integration of HF into design processes

A theory is a set of constructs that are causally linked to show how and why a phenomenon occurs. A good theory can explain a social phenomenon, and it can guide action (Friedman and Rogers 2009). In integrating HF into proactive design, the most influential theory is the socio-technical theory, which had a positive influence on HF for many years (134 positive study outcomes, Walker et al. 2008). The theory broadly suggests that both the technical and social conditions must be jointly considered for optimal system performance (i.e. people are not machines) (Walker et al. 2008). More recent theories suggest that the role of the HF Specialist in design is as a negotiator, or 'political reflective navigator' who helps to stage the workspace design process and brings appropriate design tools and techniques for HF (Broberg 2010) and can negotiate constraints (Burns and Vicente 2000). In the design literature, a similar concept called 'object worlds' suggests that design requires continual engagement of and exchange among different actors trained in different disciplines (Bucciarelli 1994). These theories have helped position HF in design as a social, negotiating process. However, they do not explain fully the process by which HF Specialists and production managers can ensure that HF is integrated into the design processes. There is therefore a need for theory, developed from empirical field data, to guide both production managers and HF Specialists who want to increase capability within an organisation for proactive HF integration in design.

1.4 There are no 'design for human factors' processes or techniques

There are a number of well-established 'x-abilities' to improve aspects of design, such as design for quality (DFQ), design for manufacturing (DFM), design for assembly (DFA), design for sustainability, design for flexibility (DFF) and design for robustness (Riley and Dhuyvetter 2000). Paul (2011) concluded after reviewing the literature, that there is insufficient consideration of HF in either definitions or implementations of the well-known DFM. Many of these design-for-x-abilities include a broad system of processes, tools and methods that show how the design process can be improved with a focus on the specific x-ability. DFQ, for example, seeks to improve the talent of the workforce, design of tasks, teamwork, techniques, technology, time and tools. A similar process for improving HF capability in design (i.e. improving design of the assembly process by increased focus on the capabilities and limitations of workers who assemble the product), however, is lacking.

1.5 Goal of paper

This paper is based on a three-year industry-research case study collaboration with a large electronics company. The goal of the collaboration was to work with senior management, engineers and HF Specialists to integrate HF into their production design processes in ways that were sustainable for them. The goal of this paper is to propose a 'design for human factors' (DfHF) theory that helps explain 'how' managers and HFS can help integrate aspects of HF into the design processes for improved operational performance.

2. Methods

A collaborative industry-research approach was used in this study, where the researcher participates 'in' the actions in an organisation, while simultaneously reflecting 'on' the actions to promote learning for both the organisation and the researchers (see Village et al. 2014a, 2014b for more information about the AR approach in this case study). This 'action research' type approach was chosen for this case study because the research question is one of 'how' action changes or improves over time and understanding the process of change or improvement from an 'inside' position to learn from it

(Coughlan and Coghlan 2002; Bamford and Forrester 2003; Lander and Liker 2007; Zink, Steimle, and Schröder 2008; Friedman and Rogers 2009). Action research, with its 'action' and 'process' focus is a recommended approach from which to develop a grounded theory with the data (Bamford and Forrester 2003; Dick, Stringer, and Huxham 2009; Poonamallee 2009).

Human factors specialists and engineers from the Human Factors Lab at Ryerson University participated with HF Specialists and engineers from the collaborating organisation. Throughout this paper, the term 'HF Specialist' will be used regardless of whether one or several are involved, and regardless of whether they are from the research team or the organisation. During the collaboration, numerous initiatives were undertaken to develop HF tools, improve integration of HF in design and involve engineers in HF (see Village 2014; Village et al. 2014a, 2014b, in press). Qualitative data from multiple sources were analysed using the classic grounded theory approach of Strauss and Corbin (1990). Grounded theory uses qualitative data to develop propositions, which then become grounded by the evidence, thus producing a theory (Carter and Little 2007). It was chosen since theory about how to integrate HF into the design process is in the early, formative stages and not enough is known about the phenomenon to state hypotheses prior to investigation (Binder and Edwards 2010). This section will describe the organisation, data collection and grounded theory analysis methods.

2.1 Collaborating organisation

The case study organisation designs, manufactures and assembles hand-held electronic devices. It provided a unique opportunity to study HF integration due to the rapid turnover of assembly lines and the large number of engineers who could participate. At the start of the collaboration, it employed approximately 20,000 people worldwide. The HF specialists ($n = 5$) and engineers ($n = 70$) were in the 'new product realization' (NPR) portion of the company. Engineers (including mechanical, manufacturing, electronic and industrial) were organised around a product line. The NPR site designs the production assembly line for new products, including design and manufacture of parts, tooling, fixtures and order of the assembly tasks. Once the assembly has proven its capability to reach production, quality and cost targets established by the engineering group, it is launched for full production to outsourcing sites in different countries. NPR engineers therefore do not have control over the number of tasks assigned to workers, workstation layout or aspects of work organisation in outsourcing locations. HF integration therefore is limited to design of parts, tooling and fixtures, and order of assembly steps. A steering committee of senior managers and directors helped to coordinate and oversee the collaboration and initiatives.

2.2 Qualitative data collection

Qualitative data were collected from mid-2010 to mid-2013 during collaboration on the many initiatives. Three sources of data were collected and later triangulated: tracking of *actions/interactions*, review of organisational *documentation*, and collection of participant and researcher *reflections*. Weekly in-person *actions/interactions* were collected with a tracking log and through note-taking of discussions and observations within the company. *Documentation* from within the organisation included meeting minutes, product designs, tooling procurement, assembly layouts, work instructions, manufacturing process documents, company newsletters and organisational charts. *Reflections* of the researchers, in the form of field notes, were documented, and reflections of participants were captured and documented after each meeting or action/interaction. Yearly semi-structured interviews were conducted with steering committee members and participants in the fall of 2010, 2011 and 2012. During the interviews, participants were asked a set of open-ended questions about what is 'helping' with HF integration, and what is 'hindering'. Regular university team meetings were also held to further reflect and plan next steps. All formal meetings, interviews and focus groups were digitally recorded, transcribed and entered into NVivo software for qualitative analysis.

2.3 Grounded theory data analysis

As suggested by Manuj and Pohlen (2011), grounded theory reporting should carefully describe the series of steps leading to the development of theory. We use Figure 1 to show the nine steps of the grounded theory approach (Strauss and Corbin 1990) used to analyse data. The steps are further discussed below.

1. *Data entry:* A total of 222 initial entries (mid-2010 to late 2012) in NVivo qualitative analysis software were used for the first portion of data analysis, each representing a transcribed action/interaction with additional researcher notes or memos. Table 1 provides examples of the empirical data.
2. *Open coding of text:* Conceptual labels were placed on text describing discrete happenings, events, statements or other instances of the phenomenon. There were 115 final codes (for example, 'compatibility', 'visibility of initiative', 'engineering-like'), which are available from the authors on request.

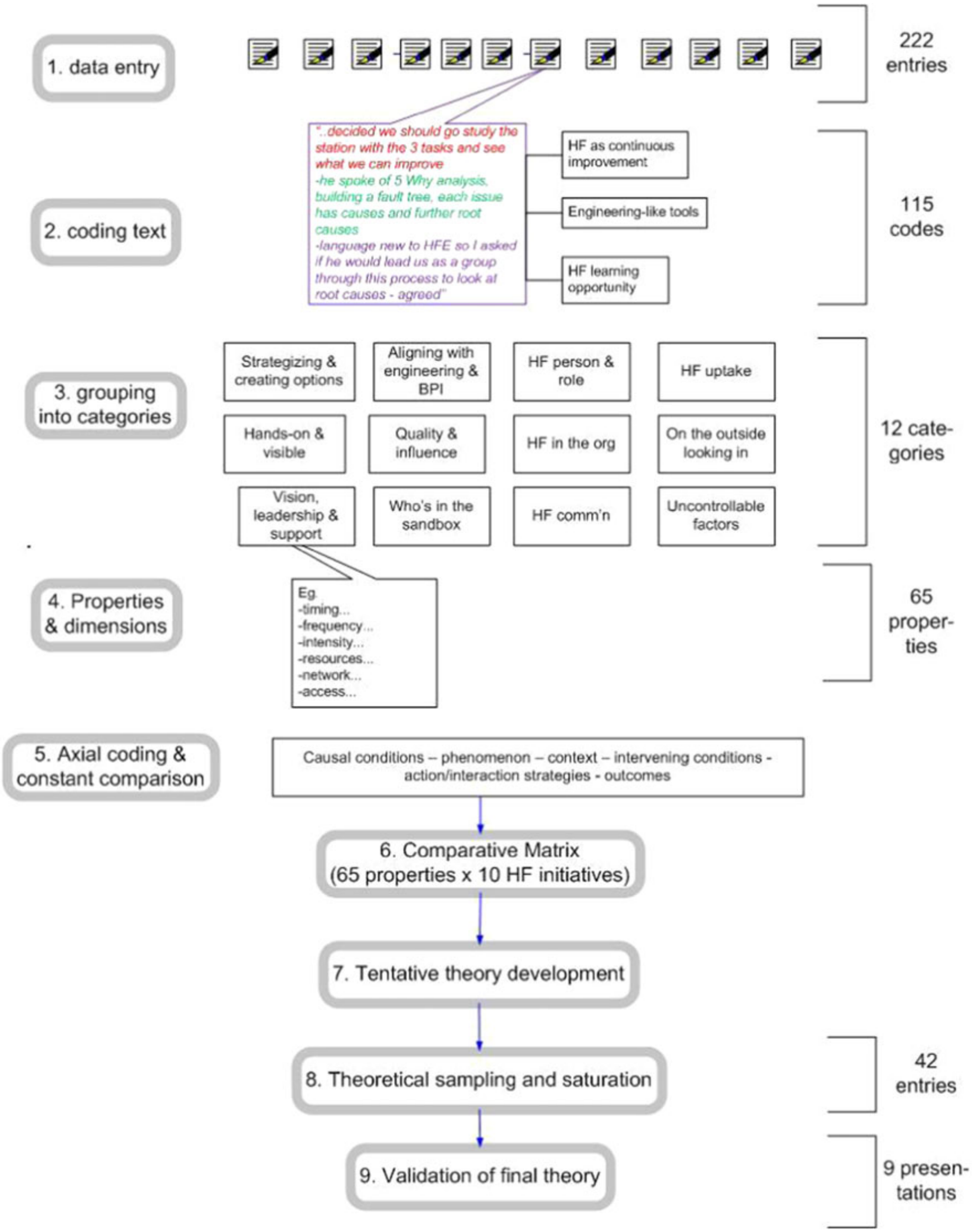

Figure 1. The nine steps of the grounded theory approach used in this study.

3. *Grouping codes into categories:* Data within each of the 115 codes was re-read, and the codes were sorted and grouped into 12 categories that were then given names.
4. *Determining properties and dimensions for each category*: For each category, the properties (attributes or characteristics of a category) and dimensions (positioning of properties on a continuum) were drawn out of the data and itemised in tables. For example, a category called 'vision, leadership and support' had properties including 'access to resources', 'participation with HF Specialists' and 'provision of contacts'. Dimensions for 'access to resources', for example, may range in 'extent' from very little to a lot, or 'frequency' from once to ongoing.

Table 1. Empirical materials ($n = 222$) used for open coding and example events and participants.

Open Coding: 222 Entries (Sept 2010–Oct 2012)				
Empirical materials	Number	Media	Explanation (examples)	Example of participants
Meetings	126	Almost all recorded, transcribed when recorded, and electronic documents	1. Meetings specific to initiatives (e.g. FMEA meetings) 2. Meetings with HFS manager and team to discuss strategies 3. Meetings to report on progress of initiative (e.g. Root cause analysis outcomes) 4. Meetings for feedback on tool (e.g. HF DFA) 5. Meetings to gather information (e.g. How quality data are reported)	• Quality engineers • IT Specialist • Product-focused engineers • HF specialists • Managers (e.g. advanced manufacturing)
Interviews	48	All recorded, transcribed and electronic documents	1. Interviews with collaborating participants and steering committee members in October 2010 and October 2011 for facilitators and barriers to collaboration 2. Interviews gathering information on specific topic (e.g. perception of metrics) 3. Interviews with directors/managers using cognitive mapping tool to determine link between HF and strategic goals	• Senior directors (e.g. Manufacturing, Continuous Improvement, Quality Systems, Advanced Process Engineering) • Managers (e.g. Project manager quality)
Steering Committee Meetings	13	All recorded, transcribed and electronic documents	1. Update on progress of initiatives in collaboration, next steps, assistance needed	• Senior directors, directors, managers, HFS
Focus Groups	16	All recorded, transcribed and electronic documents	1. Discrete event simulation findings and discussion of how this could be integrated into production design 2. Focus group to convert HF observations into DFF guidelines 3. Focus group with engineers with previous HF training to evaluate the training and determine future training needs 4. Presentation of run-at-rate data for new assembly line and prioritisation of issues for assembly optimisation	• Directors (e.g. engineering) • Managers (e.g. product-focused engineering) • Engineers (mechanical fixture designer, industrial engineer, new product manufacturing)
Observations	19	Paper converted to electronic, and some video recordings	1. Scoring HF FMEA while observing workers performing tasks 2. Observation of mock-up of new lean assembly line 3. Observations/discussions with workers regarding fixture design 4. Meeting with floor supervisors and workers to observe new assembly line and collect video	• Quality specialists, Product-focused specialists, HFS • Manager – Advanced Manufacturing Engineering • Floor supervisors, workers
Researcher Notes with each entry	222	All electronic	1. Reflections from participation in activities and planning of next steps. Written from field notes on the same day or the day following	

A constant comparison method was used to move between instances of the data to ensure that all properties were discovered.

5. *Axial coding and constant comparison*: An action-oriented paradigm as shown in step 5 of Figure 1 was used to further sort the data and develop causal relationships between conceptual categories (not actual events) to describe ‘how’ something happened. A total of 65 properties were derived from the axial coding.

6. *Comparative matrix*: In this step, a comparative matrix was designed to explore the 65 properties derived in the previous step across the 10 initiatives of the collaboration.
7. *Tentative theory development:* The 'core' category was selected and named 'Acclimate and Align with Engineering' because its properties described how the action of HF integration in the design processes came about. This new category was systematically related to other categories, and relationships were further refined conceptually with evidence in the data. Tentative relationships between categories were explored iteratively through a series of drawings and peer debriefing with the research team.
8. *Theoretical sampling and theoretical saturation*: Theoretical sampling of proposed relationships was based on 42 new entries of actions/interactions from late 2012 to spring 2013, including nine open-ended interviews with participants in the collaboration. Table 2 shows the empirical data for this stage. As a result, no initial propositions were discarded, but several were reinforced, and others were found to be less important than originally thought. At this point of theoretical saturation, the final theory was drawn, refined and prepared into presentations for validation.
9. *Validation of final theory*: Nine presentations were provided to groups for comment, including: the HF department within the collaborating organisation (1); the Engineering department and Senior Director (1) and academic researchers and peers (7). Minor refinements were made to the theory based on feedback from these presentations.

Table 2. Empirical materials ($n = 42$) used for theoretical coding and example events and participants.

Theoretical Sampling: 42 entries (Oct 2012–June 2013)				
Empirical materials	Number	Media	Explanation (examples)	Example of participants
Meetings	20	Almost all recorded, transcribed and electronic documents	1. Meeting to discuss HF role in developing charter for new HF initiative 2. Meetings to discuss how to integrate the DFF into the HF DFA process 3. Update on HF changes in new assembly line	• Senior director Engineering • Product focused engineers • HF specialists • Managers (e.g. advanced manufacturing)
Interviews	11	All recorded, transcribed, and electronic documents	1. Interviews with collaborating participants and steering committee members in October 2012 to test theoretical propositions 2. Value of HF participation in FMEA meetings 3. Review of HF DFA tool and process after assembly launch 4. Review of WEE tool modifications and next steps 5. Next steps and reflections for HFS	• Senior directors (e.g. engineering, manufacturing, advanced process engineering) • Managers (e.g. HFS, manufacturing, outsourcing) • HFS
Steering Committee Meetings	2	All recorded, transcribed and electronic documents	1. Update on progress of initiatives in collaboration, next steps, assistance needed	• Senior directors, directors, managers, HFS
Focus Group	8	All recorded, transcribed and electronic documents	1. Demonstration of WEE tool to directors and outsourcing and discussion of how best to integrate 2. Design for fixture focus group for external vendors 3. Focus group to compare scores and provide revisions to HF DFA tool 4. Focus group to validate findings from collaboration and DfHF theory	• Directors (e.g. Engineering Development) • Managers (e.g. HFS, product-focused engineering, test hardware) • Engineers (mechanical fixture designer, new product manufacturing)
Observations	1	Paper, converted to electronic	1. Review of HF issues corrected on new assembly line	• HFS • Floor supervisors, workers
Researcher Notes with each entry	42	All electronic	1. Reflections from participation and memos regarding strength of propositions. Written from field notes on the same day or the day following	

3. Results

The theory is illustrated in a process flow diagram, the structure of which will first be described in Section 3.1. The DfHF grounded theory will then be illustrated visually and evidence in support of each of the six constructs of the theory will be described using data (participant quotes and researcher notes) from different stages of the collaboration, as well as between different initiatives. The six constructs of the theory represent the core drivers of change in the case study. In the presentation of evidence, each construct is examined with both supporting evidence and consideration of contradictory evidence.

3.1 Process flow visualisation of theory

The visual representation of the authors' theory, shown in Figure 2, was drawn as a process flow diagram with arrows that indicate one construct 'leading to' another, or in 'parallel operation' in the case of the parallel lines between constructs. The shapes, arrows and lines shown in the keys at the bottom of the figure reinforce that integrating HF into production design processes is a process itself, and thus different shapes were chosen to denote different process types. There are three numbered stages, indicated by vertical separations and labels at the top of each stage. Note that the boundary of this work is the investigation of 'how' HF can be integrated, and the proposed outcomes in the dotted oval in stage 4 (i.e. improved worker health and system performance) were not validated in this case collaboration.

3.2 Summary and contributing propositions in the DfHF grounded theory

The theory's main proposition can be summarised as follows:

> When HF Specialists are acclimated and aligned to 'fit' within engineering, HF Specialists are pulled into the engineering team, and senior management hold engineers accountable for meeting HF targets (in adapted tools) since HF is perceived as a means to improve business performance. This leads to HF becoming embedded in the production design process.

Contributing individual propositions are that:

P1: Engineers and managers recognise HF as a means to improve business performance when human factors specialists acclimate to the engineering process, language and tools, and strategically align HF to the design and business goals of the organisation.

P2: When HF is recognised as a means to improve business performance, engineers 'pull' HF Specialists into the engineering team.

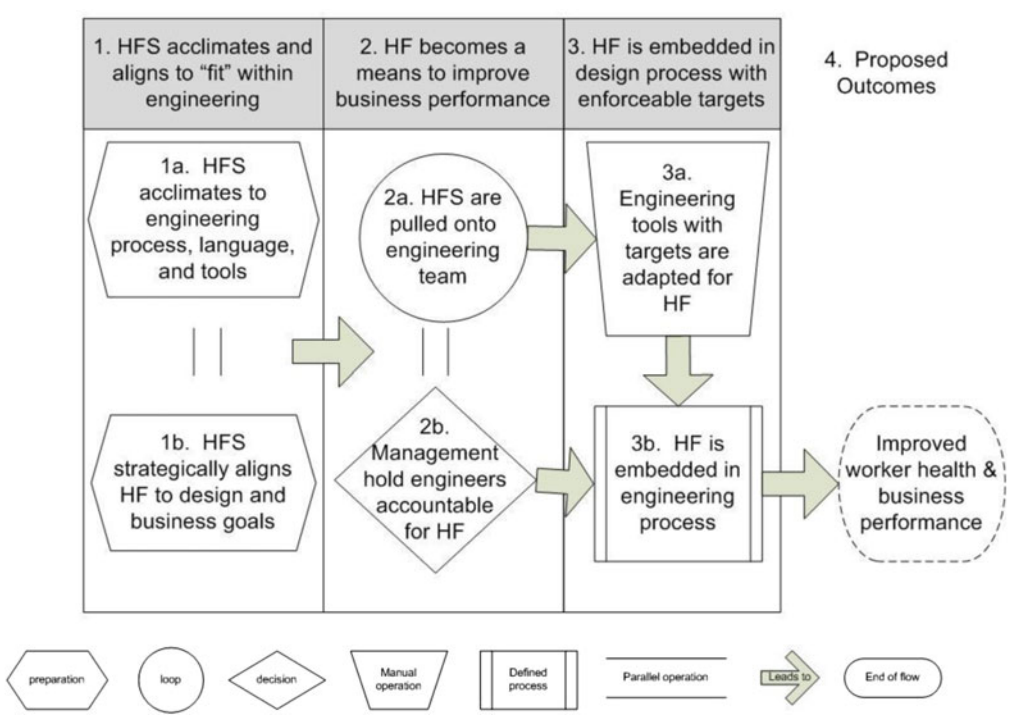

Figure 2. The DfHF grounded theory and keys to the meaning of each structural shape in the process diagram.

P3: When HF Specialists are in the engineering team, this increases requests for HF from engineers, and awareness of HF on the part of engineers.
P4: When recognised as a means to improve business performance, senior management want to monitor HF as a key performance indicator and hold engineers responsible for meeting HF targets.
P5: With HF Specialists in the engineering team, engineering tools are adapted to include HF targets.
P6: When management want to hold engineers accountable for HF, and there are HF-adapted tools with targets, then HF becomes embedded in the engineering design process.

The six propositions and illustration in Figure 2, describe 'how' HF became integrated in the engineering design process in this case study.

3.3 Evidence for the theory

Evidence for each construct of the theory shown in Figure 2 will be presented in the following sections.

1. HF specialists acclimate and align to 'Fit' within engineering

The two constructs within this first stage represent the 'core' of the theory. The theory suggests both 1a 'HF Specialists acclimate to the engineering process, language and tools', and 1b 'HF Specialists strategically aligns HF to design and business goals' describe how the HF Specialists changed focus to 'fit' within engineering design and the business goals.

1a. HF specialists acclimate to engineering process, language and tools

Four key properties describe this construct. First, the HF Specialists had to gain an understanding of the engineering design process and how engineers work (for example, having detailed plans with deliverables and return-on-investment). Second, the HF Specialists had to learn the engineering language and be able to communicate HF in engineering terms. Third, the HF Specialists had to become familiar with tools used by engineers. Fourth, the HF Specialists had to be visible and able to demonstrate change. The data analysis showed that when the HF Specialists were not acclimated, they had limited success in working with engineers, and being supported by senior management. By contrast, as the examples below will illustrate, as acclimation increased, there was increased interest in HF from engineers and management, access to engineering processes, inclusion in design decisions and recognition of the value of HF.

At the beginning of the collaboration, the HF Specialists reported to an OH&S Manager, in another building, and most of their work was reactively assessing workstation problems in response to an incident/injury report being filed by a worker to OH&S. While one of the HF Specialist's goals was to integrate HF into production design, the HF Specialists had few connections with the engineering department and had experienced little success. Generic ergonomic guidelines for workstation design had been developed prior to the collaboration, but few engineers were aware of these and they were not being used. The HF Specialists stated at this time:

> they (engineers) are capturing issues – I don't see what they are – I don't have access to them – it may be that some involve a HF component but we (HF specialists) never know about it

> I've been at (the company) 4 years and it feels like I'm only starting to get my foot in the door (with engineering).

The HF Specialists attempted to get 'in the door' by emailing all engineers responsible for new assembly designs stating that they (HF Specialists) wanted to be more integrated in the design process. Later, a director offered access to the project list in his department and stated that the HF Specialists were welcome to get involved with any that pertained. However, neither of these efforts resulted in any action. The HF Specialists had difficulty in understanding what the projects were, what the HF role might be and how to go about getting involved. Likewise, the engineers and director did not know what to expect from the HF Specialists.

Researcher notes from observations during early meetings with HF Specialists and engineers discussed this need for acclimation to engineering:

> Working with engineers on a design problem requires a lot of technical knowledge about the process, tools, parts, materials etc. It's not enough to describe an awkward posture using a tool – one needs to understand with some detail what the tool is accomplishing, how it is designed, tolerances, why a tool and not a hand (too much force, too little precision, chance of scratching), how the alignment of the part matches the tool – how the material pick-up integrates with the tool – this deeper understanding is necessary to participate in improving the design – this means spending time and being part of these discussions– for HF to be seen by engineers as a legitimate help – it has to provide a new perspective on their problems. (Researcher notes)

The acclimation process for the HF Specialists involved spending sufficient time with engineers in meetings and on the NPR floor to understand the design process, the people involved, the timelines, the engineering goals and how HF could contribute. The more the HF Specialists learned about the engineering process, the more apparent it became that they needed to frame HF in engineering language. For example, rather than talking about workers having sustained pinch grips when inserting a part (a risk factor with an OH&S focus), HF Specialists discussed how assembly difficulty affected cycle time and quality defects (engineering terminology with a performance focus). Using terms such as 'value-added' and 'non-value added' led to immediate interest if the HF Specialists could demonstrate how reducing a reach could reduce non-value added time (even though it reduces load on the worker too).

The acclimation process for HF Specialists also involved learning typical engineering tools, such as failure mode effects analysis (FMEAs), root cause analysis, Hoishin, Gemba walks, Kaizen, etc. Half way through the collaboration, one HF Specialist opted for six days of intense training in engineering tools related to Six Sigma. As the HF Specialist began to participate in these meetings and activities and use these engineering tools, they not only became more familiar with the language and tools, but also began to see how HF could 'fit' and contribute to the engineering goals, instead of a singular focus on reducing injury. The HF Specialists needed to think about how HF could help with minimising variation, minimising fatigue, reducing quality problems, enhancing workers' ability to detect quality problems, reducing errors and designing such that operators can consistently assemble products in a way to give good quality. These all had HF implications, but required the HF Specialist to change their focus.

The HF Specialist also needed to be visible and actively participating on the shop floor to 'fit' within engineering. When participating in discussions with engineers, in Kaizen activities with operators, or in Gemba walks with senior managers, HF was recognised by engineers as a positive influence on design goals. Part way through the collaboration, the HF Specialists physically moved to the engineering floor with closer access to the shop floor. This increased access to discussions, documents, data and meetings with engineers. Towards the end of the collaboration, the HF Specialist stated:

> I say it took me over a year to learn what engineers were doing, who's who, the language, who reports to who, how does quality fit in, what is a Kaizen – this all has to be absorbed to know where you're effective

1b. HF specialists strategically aligns HF to design and business goals

In conjunction with acclimating to engineering, the HF Specialists needed to align HF with design and business goals in the organisation. This means that HF needed to directly address operational goals, and that it has to fit with high priority initiatives. There were numerous quotes to choose from at different times in the collaboration and from different senior managers and directors who illustrated this:

> we would like to cooperate but it has to be aligned with the priorities we have and our business objectives.

> Good HF would be measured by the product being manufacturable – process capability measures (eg. tracking defects).

A cognitive mapping initiative (see Village et al. 2012; Village, Salustri, and Neumann 2013; Village et al. in press) was critical for helping the HF Specialists understand the perceptions of senior management with respect to how HF was connected to the main strategic goal in the organisation of improved product quality. Management perceived that reducing worker fatigue and improving their consistency of performance, through optimal systems design of the assembly, was directly related to improving product quality and reducing quality losses. This was illustrated in the following quote from a manager:

> If you could develop a model that can reduce fatigue and increase repeatability this will have a direct impact on quality and productivity

When HF initiatives 'fit' with high priority initiatives, such as a new focus on the Toyota Production System and continuous improvement, they were more readily adopted. For example, the HF Specialists suggested that the ergonomics change team (workers and supervisors with some training in ergonomics of workstation and assembly set-up) conduct a Hoishin to look for work improvements. This was readily supported by Senior Directors as part of their new emphasis on business improvement programmes. Workers were trained and the HF Specialist stated that the HF Hoishin became locked in and was spreading to other sites because it was part of the new strategic thinking and safety culture. This 'alignment' with a current business programme made HF a good 'fit'.

To illustrate with an example, one researcher was developing a workstation assessment tool that the organisation could use to proactively design workstation layouts. There were several versions of the tool over three years (Greig et al. 2013). Initially, the tool tracked hand travel at a workstation, with the idea that less is better for the worker. There was little involvement from engineers in this version because they did not see how the new tool could 'fit' with their existing tools and processes. The second version included shoulder loading to indicate fatigue, but as with the first did not contain quantifiable thresholds or metrics. Interest from engineers increased when reach zones and red/green colour-coding were added. This reinforces the notion of being visible, quantifiable and having thresholds. Interest from engineers further increased when the tool was renamed the 'workstation efficiency evaluator', and it included measures in the time domain that could predict cycle time and non-value added tasks from a workstation drawing. At this point, the tool was seen as an aid to predict both load on the worker, but also cycle time and potential imbalances between workstations. The HF portion of the tool was now aligned to help achieve assembly design goals.

Another example illustrates the challenges for HF Specialists in adapting and aligning to an engineering environment. In attempts to piggyback on an internal project designed to improve effectiveness of FMEAs, the HF Specialists proposed an initiative to develop a HF-FMEA (see Village et al. 2011). At that time, however, the organisation was undergoing downsising and a turnover of managers. The HF Specialists were advised by engineers to develop a 'charter' document for the HF-FMEA that outlined deliverables, timelines and return on investment (ROI). Being from the OH&S department, the HF Specialists were unaware how to define HF outcomes in ROI terms, and seek engineering sponsorship for the initiative. They felt that this need for a charter was an unnecessary roadblock. However, the engineers were merely expressing that since many projects were being eliminated, if the HF-FMEA was not positioned as an engineering project with a sponsor and ROI, then it would not survive as an engineering priority. Despite initial challenges to draft charters, from that point forward all HF initiatives were put into engineering charters to ensure they had sufficient support within engineering and the appropriate participants were involved.

As shown by the evidence above, the first proposition of the theory states:

P1: Engineers and managers recognise HF as a means to improve business performance when human factors specialists acclimate to the engineering process, language and tools, and strategically align HF to the design and business goals of the organisation.

2. HF becomes a means to improve business performance

As shown in Figure 2, when the HF Specialists acclimated to the engineering processes, language and tools (1a), and aligned HF with strategic and business goals (1b), this led to two constructs that facilitated HF becoming a means to improve business performance and these occurred in parallel. The first is that the HF Specialists became a member of and resource to the engineering team (2a), rather than a separate entity outside of engineering. The second is that senior managers wanted to hold their engineers responsible for HF (2b) because it was a means to improve business performance.

2a. HF specialists are pulled onto the engineering team

An ongoing theme in the collaboration was whether the HF Specialists and HF knowledge resided outside engineering, trying to 'push' its way into the design process from a health and safety focus, or whether it was being 'pulled' into the engineering team because it was helping achieve their goals. The data and examples below will show that when HF knowledge and expertise was pulled by engineering, the application was quicker and more effective. Early in the collaboration, there were tendencies both by engineers and by HF Specialists to want to separate 'engineering' issues from 'HF' issues. For example, during one FMEA meeting when the HF discussion of a task seemed to be slowing progress, the FMEA lead suggested that in future meetings the 'HF issues' be reported in the last 15 minutes of every meeting, rather than as each arose during the meeting. The researchers and HF Specialists recognised that this would create a silo effect and make the HF issues separate from engineering, and perhaps even perceived as a problem rather than having HF become part of the solution. We therefore requested that HF be considered alongside engineering concerns with discussing each potential quality problem in ongoing meetings.

Another example illustrates the effectiveness of a 'pull' for HF versus a 'push'. As previously mentioned, the HF Specialists had developed ergonomic guidelines for workstation design prior to the collaboration and given these to industrial engineers. However, the guidelines were not being used. Years later in the collaboration, when HF Specialists and engineers were working together on a common goal of improving the camera insertion step of a new assembly, engineers realised that the layout of materials on the work surface was affecting ease of camera insertion. A director, realising that they lacked a proactive process for optimal workstation design, quickly tasked the industrial engineer with documenting a process. The industrial engineer, in turn, requested a checklist from the HF department – the same one that the HF Specialists had been unable to 'push' in previous years. This illustrates that when engineers recognised that HF would help improve system performance, the HF information was quickly 'pulled'.

The data analysis showed that increasing teamwork led to more requests for HF information, a more extensive network in engineering, and increased opportunities for HF Specialists' participation in the design processes. Being on the team helped the HF Specialists become aware of new products and processes earlier, thereby also improving the effectiveness of the HF initiatives. Working together helped the HF Specialists learn how engineers work, their time demands for HF solutions, and the best way to provide appropriate answers to questions. In later stages of the collaboration, for example, the HF Specialists stopped writing lengthy reports (common when reporting to OH&S), and started providing 'issue recommendations and sign-off' within engineering tracking documents. At the beginning of the collaboration, when the HF Specialists were separate from engineering, they did not know about or have access to these tracking documents.

Engineers also became acclimated to HF when working together as a team, and saw the benefits. Getting on the team, making the work visible and reporting in a timely and appropriate manner all led to increased requests for assistance from engineers. Both the HF Specialists and various engineers made statements about the team approach:

HF Specialist:

> Trying to mix with those guys in a team environment – the whole integration is about the team – we're identifying the HF component – but it's an engineering process – and we're there as part of the team

Engineer:

> I think he's become more of an engineering resource – he used to be more for ergo and line set-up and dealing more with like capital – chairs, table heights, should we use footstools – but now he's more in with engineers – helping us design this – help us modify this, and part of fixture design process – where he should be

Therefore, the second and third propositions state:

P2: When HF is recognised as a means to improve business performance, engineers 'pull' HF Specialists into the engineering team.

P3: When HF Specialists are in the engineering team, this increases requests for HF from engineers, and awareness of HF on the part of engineers.

2b. Management hold engineers accountable for HF

This section shows that HF integration into design required management to hold engineers accountable for HF. This managerial accountability for HF only occurred, as illustrated in the theory in Figure 2, when the HF Specialists were acclimated to engineering and aligned with design and business goals. This section will provide examples where there was lack of accountability and therefore HF integration, and where accountability led to integration.

In one initiative to proactively integrate HF into the design processes, engineers were upgrading DFF guidelines and requested inclusion of HF-specific DFF guidelines. The engineer responsible developed a process chart, included the HF guidelines and included a sign-off on the guidelines by the HF Specialists for any new fixture designed or procured. Despite the teamwork, the guidelines and the process, for the next year these were all ignored by engineers. The HF Specialists assumed that HF was embedded in the process, but the process collapsed because it lacked accountability from senior managers.

By contrast, another initiative between HF Specialists and engineers involved development of a HF DFA tool. The tool arose when HF Specialists were working on the team with engineers and together realised the overlap between ease of assembly, HF and assembly quality. When data were collected using the new HF DFA tool on an early assembly build and shown to senior management and the engineering team, the scores confirmed tasks that both engineers and workers knew were problematic. HF was now tangible, measurable, could demonstrate change and aligned with engineering goals of improving assembly quality. As a result, senior management perceived that HF could be a means to help achieve business goals, and they readily made the HF targets one of their key performance indicators (along with defect rate, cost and yield). Management then monitored HF DFA scores and held their engineers accountable for meeting HF targets in each subsequent product build. When the Senior Director was asked where in the process this might 'fit', the response was:

> ... hand it off to mechanical engineers in the program, make it part of the build – a deliverable, it's measurable and I can measure – (we) need objective ways of evaluating and knowing where to focus

Therefore, in our collaboration, there was 'some' support 'in principle' from senior management in early and mid-stages (by developing a steering committee and attending meetings), but this did not truly result in HF initiatives being adopted or sustained in processes. The DFF example showed support from engineers involved in the process, but collapsed without accountability from senior management. When the HF Specialists could demonstrate for senior management the value of HF to achieve business goals (as in the DFA example), this led to HF becoming a requirement from senior management. A shift from support 'in principle' to support 'in practice' caused a tipping point – a shift in attitude by senior management in the case study. We suggest that this more refined definition of accountability is necessary for HF to become embedded in the engineering processes.

Therefore, the fourth proposition of the theory states:

P4: When recognised as a means to improve business performance, senior management want to monitor HF as a key performance indicator and hold engineers responsible for meeting HF targets.

3. Human factors is embedded in a design process with enforceable targets

The third stage of the theory proposes that in order for HF to be integrated into the design processes, there needs to be a measureable way to communicate HF issues and demonstrate improvement towards business goals. The theory shows that when HF Specialists are aligned to help improve business goals (1b in Figure 2), and senior managers perceive that HF will improve business goals (2b), then the key that locks HF into the design process is the adaptation of engineering design tools to include enforceable HF targets (3a).

3a. Engineering tools with targets are adapted for HF

This section will show the importance of adapting engineering design tools to include enforceable HF targets. In this case study, there were examples where lack of a tool hindered progress towards HF integration in design. We also have several examples where the tool adapted for HF came first, and was subsequently locked into the design process.

The following researcher notes from early in the collaboration describe the struggle to figure out how to proceed in the absence of a HF tool. The HF Specialists had helped identify issues related to HF, but were not sure how this could lead to involvement in the next assembly design cycle:

> We can't just indicate problems – we need tools for sustainable processes. They see value in our task break down and value added classifications – will this help with solutions on the line? Will it help change their processes down the road with other products? We still need to embed HF into analysis – we've provided some indications of problems and how that ties into cycle time and balancing – a key of combining engineering and HF – but should the HF be more explicit – how will this work going forward? (researcher notes)

In early discussions about improving the fixture design process (discussed in section 2b), the engineer asked one HF Specialist '*how would you 'qualify' a fixture, now that you have sign-off?*' The researcher notes indicated that the HF Specialist did not know how to respond. This suggests that getting HF established in a process requires a tool. Simply adding a HF check in the process (i.e. the HF Specialist assesses and signs off), or collecting HF concerns, does not specify what precise HF issues are to be evaluated, how they are evaluated, what is reported, who gets the information and where those lessons go. However, if a HF tool is consistent with existing engineering design tools, then it is more likely to answer appropriate questions, and lead to permanent documentation, lessons learned, benchmarking and best practices.

During this collaboration, we identified a lack of appropriate proactive HF tools adaptable to this intensive assembly environment where the focus is not upper limb injuries, but assembly quality and operator consistency. The adapted tools had to focus on assembly design goals and be quick, visible and quantifiable. One engineer stated:

> (we) 'need to make sure the methodology is quick enough and nimble enough to not overload people when doing new product realization'

Another engineer stated the need for something visual and engineering-like

> As designers we want a quick reference – quick schematic – ideas are floating around in our head as we design

A good tool can then lead to targets. A senior director stated:

> (we) 'like dashboards, with red/yellow/green – Directors get 12 presentations/hour – you've got 5 minutes, so you want data to jump out'

By the end of the collaboration, we had adapted five engineering design tools to include HF (HF–FMEA, HF–DFA, HF–DFF (fixtures), workstation efficiency evaluator and HF-Kaizen) and these were integrated into different stages of the assembly design process (see Village et al. 2014a, 2014b). The tools provided quantifiable metrics aligned with the business and assembly goals. An example quote from an engineer on review of a demonstration with the HF-DFA tool exemplifies this:

> HF that accommodates KPIs (key performance indicators, or targets) fits well with DFA – along with cost, scrap, etc. – this fits in perfectly

The results of this section lead us to the fifth proposition, which states:

P5: With HF Specialists in the engineering team, engineering tools are adapted to include HF targets.

3b. HF Embedded in engineering process

The five constructs of the theory discussed above and illustrated in Figure 2 led to the overall goal of HF being embedded in the engineering design process. We have several indicators of HF integration. The self-reported percentage of time the HF Specialists performed proactive HF work (in design stage) increased from 3.5% in 2010, to 72% in 2013. The number of engineers with whom the HF Specialists worked directly increased from 15 in the first year, to 70 in the third. From documentation and observation of subsequent assembly design cycles, the HF Specialists participated with engineers in all assessments and solution development for the new product lines. Changes were documented to parts, processes, materials and fixtures arising from the inclusion of HF in these early design stages.

In addition, there was evidence towards the end of the collaboration that engineers, managers and others had increased awareness and application of HF early in the design processes. The Senior Director of Engineering involved in the third stage of the collaboration stated that he was ‘skeptical’ at first of the value of HF and did not participate directly for the first two years. However, he later became a ‘convert’. He stated:

> I’m a convert – I thought (the HF Specialist) is a tables and chairs guy. I didn’t understand how it (HF) impacted our process – engineers think you’re as capable in inspection of a screw at minute 1 as at minute 360 – and it’s not true – one of the things I’m missing in my analysis of the system is the variability of the human element – things we don’t know – I’m a road to Damascus convert – it’s like night and day now for me now

This quote strongly supports the core tenet of our theory – that the HF Specialists needed to acclimate to engineering and align HF with design and business goals. This was pivotal for gaining access to the engineering team and being perceived by senior managers as a means to improve system performance. The other necessity was the adaptation of engineering design tools to include HF in such a way that they can be enforceable targets.

Two examples will be used to illustrate the changes among managers, engineers and HF Specialists from the beginning to end of the collaboration. At the beginning, the Ergonomics Manager tasked the HF Specialist in manufacturing to develop a process diagram showing where they wanted HF to fit within the engineering design process. The HF Specialist was unsure how to go about the task, did not know which engineers to involve, did not have engineering management support and had no idea about how to embed HF in an engineering design process they did not yet understand themselves. This work item was not completed at this time. By contrast, towards the end of the collaboration, the Senior Director of Engineering requested a meeting with HF Specialists to develop a ‘Utopian Workstation Layout’. Several things about this initiative demonstrate change compared to before the collaboration:

- The Senior Director of Engineering approached the HF Specialists, now in the engineering department, with an engineering project idea realising the value of HF towards the business goals;
- HF Specialists used engineering methods and documentation systems to draft an engineering charter to monitor timelines, deliverables and ROI;
- HF Specialists approached and coordinated an appropriate working group of engineers for the initiative, including those from outsourcing companies in other countries;
- HF Specialists chaired the meetings, prepared minutes and collected data visibly on the shop floor as appropriate for the initiative;
- The HF Specialists worked with engineers to create a unique ‘tool’ incorporating HF into early workstation design requirements, with HF targets and
- The HF Specialists took ownership of the project and had a proactive vision as to HF application in early production design.

This example illustrates the constructs of the design for HF theory. HF became integrated in the design process when the HF Specialists were acclimated and aligned to fit within engineering, they were on the engineering team, engineering tools were adapted for HF with targets, and management held engineers accountable for the HF targets. The data support the sixth proposition of the theory, which states:

P6: When management want to hold engineers accountable for HF, and there are HF-adapted tools with targets, then HF becomes embedded in the engineering design process.

4. Discussion

The DfHF theory describes the developmental process of how HF came to be proactively integrated into assembly design processes in a large electronics manufacturing operation. It has been grounded with three years of data documenting the process, and participation of 70 engineers and five HF Specialists in a longitudinal collaboration. Such ‘embedding’ in an organisation’s design process and culture is similar to Wilson’s (2012) statement that all good HF research should take place 'in the wild' of real operations since HF must be understood in a setting or context, which is increasingly that of complex socio-technical systems.

Christiansen (2011) suggests that the 'core tenet' of a theory should explain the main actions and most of the variation in the data. In the DfHF theory, the core tenet is a change in positioning of HF and the HF specialists in the organisation from a predominately health and safety focus, to align with design, operations and strategic business goals. In essence, the goal is to move HF out of a 'side-car' health and safety function in HRM, into the gap between HRM and operations management (Neumann and Dul 2010). The DfHF theory illustrates how HF Specialists needed to learn the design process, engineering language and tools, and work visibly alongside engineers on the floor and in design activities using the engineering systems (e.g. reporting and project documentation). HF Specialists also needed this understanding to help position HF as a means to improve business performance. In this case study, the HF Specialists were then able to strategically align HF as a means to reduce operator fatigue, improve consistency of performance, reduce wasted motions and improve quality – rather than exclusively as a means to reduce injuries. With alignment, engineers and managers realised that HF was a resource to help improve business goals and 'pulled' HF Specialists onto the engineering team. To be sustainable in the design process, however, the HF Specialists also needed tools that would provide quantitative targets and measures that could be used, like engineering tools for communication, comparison, continuous improvement and benchmarking. Adapting engineering tools to include HF was effective because they are already focused on business goals, and are familiar to engineers. With HF targets focused on the business goals, senior managers held engineers responsible for the HF targets, locking HF into their design processes in a sustainable way. Rather than being a separate entity, HF is now a key resource to engineering design and involved in all new assembly design processes.

'Design for HF' deserves its place alongside other x-ability design processes since it explains a way to improve HF aspects of design processes. It has the potential, with further development of tools, techniques and processes, to become a broad movement to improve system performance, similar to DFQ. However, it requires a shift in perspective for HF practitioners, production engineers and researchers alike, as well as an operations management shift to better utilise the skills of HF Specialists in production design. It also requires more research on tools, methods and metrics to optimise human performance, such as minimising fatigue, improving consistency, improving recognition of quality problems and enhancing flexible assembly capabilities. Zink (2006) suggested that the HF science needs a paradigm shift, away from compliance with H&S laws, to a more positive economic mission and towards enhancing (or 'maturing') the role of the operator in the system. Woods and Dekker (2000) describes that HF Specialists need to shift their paradigm from one of evaluating current systems, to being able to predict 'envisioned new worlds' in order to anticipate failures earlier in the design stages. Woods and Dekker (2000) suggests that the HF tools and techniques of the past era are too simple and applied too late in the design process for the complex and dynamic systems of this era. This is not to suggest that HF Specialists should abandon their role of minimising injury, but it does suggest that there are far reaching opportunities to do both. As Dul et al. (2012) point out, HF Specialists have great potential to contribute to the design of systems, but to contribute they must demonstrate their value, especially with respect to performance, to the main stakeholders. The DfHF theory describes how this was done and provides guidance and analytic transference of relevant elements to others interested in HF applied to production systems design.

Other researchers have also reported support for some of the constructs in the DfHF theory. The importance of linking HF to strategic goals has also been identified by Berlin (2011) in an interview study with four companies, by Zink, Steimle, and Schröder (2008) working in a 6000-person automotive plant, and by Munck-Ulfsfält et al. (2003) in their successful Volvo ergonomics programme. Both Eklund (1997) and Wilson (2012) reported that HF became embedded within the engineering group when it supported design, engineering and maintenance of the system. Several researchers have discussed borrowing from engineering tools, such as the root cause analysis, to demonstrate that improving task performance directly will lead to better acceptance of HF innovation (Gawron et al. 2006; Carayon, Alvarado, and Hundt 2007; Falck and Rosenqvist 2012; Village et al. 2014a, 2014b). Similar to our process, others have suggested that the first phase of integration of HF into design cycles requires considerable data gathering and acclimation (Kirwan 2000; Seim, Broberg, and Andersen 2012). In attempting to integrate HF into the defense industry, Waterson and Kolose (2010) reported that HF Specialists overcame the barrier of being seen as a 'tick box' item by trying to adopt the mindset of the engineers, and modifying the way they express, share or translate HF data. This supports our findings that the HF Specialists were getting more participation from engineers when they aligned HF with engineering language and goals.

Our theory has overlap with Broberg's (2010) description of HF Specialists as a political reflective navigator – or a change agent. The HF Specialists in this case spent at least a year acclimating to the engineering process, language and tools in much the same way as Broberg suggests. It is possible that the use of 'navigation tools' described by Broberg (2010) that assist the HF Specialists to take on the role of workspace designer would have been helpful in our collaboration. We recommend the need for more research to develop tools and techniques for HF Specialists to navigate the design process, the organisational structure and the organisational climate to reduce the time for this acclimation. In our collaboration, a process map of the design process was developed and used in workshops with engineers and HF Specialists as a means to identify opportunities to integrate HF into the design processes (Lim et al. 2014). Other such navigation tools and techniques are needed.

Our DfHF theory resonates closely with both the absorptive capacity theory (Cohen and Levinthal 1990) and the diffusion of innovations theory (Miles 2012). Absorptive capacity theory suggests that learning is cumulative and greatest when the object of learning is related to what is already known (i.e. shared language). The diffusion of innovations theory suggests that innovations tend to be adopted more quickly when they are compatible with existing values, past experiences and current needs, can be tried out or played with by potential adopters, and are observable (Miles 2012). In the DfHF theory, the core tenet suggests that HF Specialists need to acclimate and adapt to 'fit' with engineering processes, language and tools. This helped engineers to assimilate HF as 'new knowledge' because it was in a similar format to their engineering knowledge base and was compatible with their values and experiences, as well as having tools that are observable and can demonstrate change.

4.1 Methodological discussion

The DfHF theory is based on a longitudinal case study over three years, allowing recurrent patterns of behaviour to be observed. The case study method is preferred when 'how' and 'why' questions are posed, when the investigator has little control over events, and when the focus is on studying phenomenon within a real life context (Yin 2009). Although it is a single case study conducted in an admittedly unique new product manufacturing design environment, the thick description lends itself to transferability to other contexts. Further testing of the individual constructs of the theory (such as acclimation to engineering processes) is needed as is further testing of its applicability to other organisational environments. We were working with an existing production design process and did not have influence on the broader work organisation and workstation design, which are outsourced to other countries. Pre and post interviews with the same participants were not possible due to significant organisational downsizing and layoffs. However, the fact that the HF efforts continued in the face of such downsizing reinforces that the constructs were working in this case, regardless of changing personnel and senior management. Having HF-adapted tools and enforceable targets in the design process made it more likely that HF integration would continue in subsequent design cycles, compared with needing a HF person or process check-off. We collaborated with a large number of varying groups of engineers and managers, minimising any potential bias resulting from a single relationship or 'champion' (for example, with a senior manager, or group of engineers). The multiple initiatives within the case study also strengthen the study design, similar to having multiple embedded cases, since we could contrast strengths and weaknesses of each initiative.

We found the grounded theory approach useful, both as an organised set of principles and methodology, and as an organic process of theory emergence (Stillman 2006; Suddaby 2006). Stillman (2006) suggests that using a grounded theory methodology within an action research approach is rooted in the systems perspective, with the theoretical power and potential for systemic change. Grounded theory is increasingly being used in operations management and business research (Binder and Edwards 2010; Christiansen 2011; Randall and Mello 2011). However, despite calls for more qualitative methodology in HF research and practice (Hignett and Wilson 2004), its use is rare.

4.2 Implications of DfHF theory

The main implication of the DfHF theory is that for HF Specialists to work with engineers to integrate 'human' aspects into the production design process, they need to acclimate and align HF with design and business goals in the organisation. This may require an organisational shift to move HF Specialists out of an OH&S function in HR, and encourage their deployment directly in engineering production design. Production engineers can facilitate the alignment of HF with the design process and the strategic goals of the organisation by working together with HF Specialists and providing apprenticeship-like in-house training. As others have suggested, when HF Specialists who work in manufacturing are given the opportunity to learn about the engineering design process, language and tools of engineering design, their unique specialisation in human capabilities can contribute to improvements in production design (Mital 1995; Burns and Vicente 2000; Strasser and Zink 2007; Wells et al. 2007). Companies employing HF Specialists should also provide more internal knowledge of the organisational goals and structure, and support internal training. Mital (1995) suggests that the HF Specialists can influence the manufacturing process, but they must be able to convince other members on the team that HF requirements are as critical as cost and other requirements, and be able to suggest how these conflicts with other factors can be resolved. This requires an in-depth knowledge of manufacturing (Mital 1995).

More education is recommended for HF Specialists in engineering design language, processes and tools. Education is also recommended for operations managers on the potential benefits of including HF aspects in the design of new production systems. With the exception of the sub-discipline of industrial engineering, it is rare for engineering departments to have HF courses or HF research, especially in Canada. More research is recommended that combines engineering and HF domains such that engineers can make use of HF knowledge, and HF research is more relevant to the worker performance priorities of production designers. For example, there are research gaps on HF issues related to indicators of fatigue and ways to minimise fatigue to maintain performance, methods for maintaining consistency of operator performance and ways to improve operator detection of quality deficits. A closer focused collaboration between the technical sciences (engineering, management and business) and the HF-related sciences (which are frequently in the health, psychology or applied sciences) could lead to quantification of human aspects (such as fatigue, learning, error detection) that could improve operational models and simulations. Since there are far fewer HF Specialists than engineers working in production design, engineering design tools adapted to include HF should also be available and taught to practicing engineers and their managers.

5. Conclusions

The DfHF grounded theory provides empirical evidence that fills a gap by illustrating 'how' HF aspects can be integrated into the production design process to improve worker performance and well-being. HF Specialists and production managers can facilitate HF integration by shifting HF Specialists from a predominately OH&S role in HR, into a direct operations and production role alongside engineers. Working with engineers facilitates acclimation of HF Specialists to the design process and engineering language and tools. It also helps HF Specialists know why and how to align HF with strategic goals and adapt engineering design tools with HF targets. Managers hold engineers accountable for meeting HF targets because they are aligned with business goals, thus embedding HF into the design process.

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