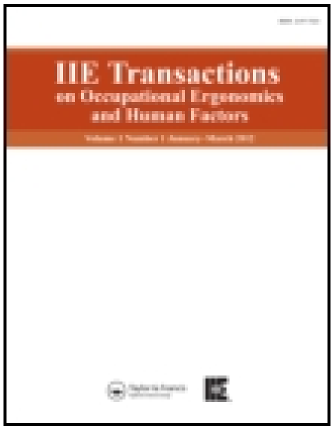




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# Adapting Engineering Design Tools to Include Human Factors

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**ORIGINAL RESEARCH**

# Adapting Engineering Design Tools to Include Human Factors

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**OCCUPATIONAL APPLICATIONS** In a longitudinal collaboration with engineers and human factors specialists at an electronics manufacturer, five engineering design tools were adapted to include human factors. The tools, many with required human factors targets, were integrated at each stage of assembly design to increase the proactive application of human factors. This article describes the process of adapting the five tools within the collaborating organization. Findings suggest 12 key features of human factors tools, most importantly that they "fit" with engineering processes, language, and tools; directly address business goals and influence key metrics; and are quantifiable and can demonstrate change. To be effective in an engineering design environment, it is suggested that human factors specialists increase their understanding of their organization's design process, learn which tools are commonly used in engineering, focus on important metrics for the business goals, and incorporate human factors into engineering-based tools and work-system design practices in their organizations.

**TECHNICAL ABSTRACT** ***Rationale:*** Design engineers use diverse tools in design, but few incorporate human factors, even though optimizing human performance can further improve operational performance. There is a need for practical tools to help engineers integrate human factors into production design processes. ***Purpose:*** This article demonstrates how five engineering design tools were adapted to include human factors and were integrated into design processes within the case study organization. It also provides features of an effective human factors tool and recommendations for practitioners. ***Method:*** A longitudinal collaboration with engineers and human factors specialists in a large electronics manufacturing organization allowed in vivo adaptation and testing of various tools in an action research methodology. Qualitative data were recorded from multiple sources, then transcribed and analyzed over a 3-year period. ***Results:*** The adapted tools integrated into each stage of the design process included the human factors process failure mode effects analysis, human factors design for assembly, human factors design for fixtures, workstation efficiency evaluator, and human factors kaizens. Each tool had a unique participatory development process; 12 features are recommended for effective human factors tools based on the findings herein. Most importantly,

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tools should “fit” with existing engineering processes, language, and tools; directly address business goals and influence key metrics; and be quantifiable and demonstrate change. ***Conclusions:*** Engineers and management responded positively to the five tools adapted for human factors because they were designed to help improve assembly design and achieve their business goals. Several of the human factors tools became required targets within the design process, ensuring that human factors considerations are built into all future design processes. Adapting engineering tools, rather than using human factors tools, required a shift for human factors specialists, who needed to expand their knowledge of engineering processes, tools, techniques, language, metrics, and goals.

**KEYWORDS** Human factors, proactive ergonomics, assessment tools, assembly design, engineering design tools, continuous improvement



## INTRODUCTION

Design engineers learn and use diverse tools to design and optimize assembly production systems, e.g., failure mode effects analysis (FMEA), value stream mapping, root cause analysis, design for manufacturing and assembly, five whys, and six sigma (Chen et al. 2010). However, few of these tools incorporate human factors (HF) or ergonomic considerations (terms used interchangeably here) even though there is evidence that improving human performance can further improve operational performance (Neumann & Dul, 2010; Thun et al., 2011). Two reports were found of modifications to the FMEA to consider operator health instead of product or process failure modes (Barsky & Dutta, 1997; Munck-Ulfsfalt et al., 2003). Zink et al. (2008) also discussed adapting the continuous improvement shop floor tool called kaizen to include HF. Several researchers have discussed borrowing from engineering tools, such as root cause analysis, to demonstrate that improving task performance directly will lead to better acceptance of HF innovation (Gawron et al., 2006; Carayon et al., 2007; Falck & Rosenqvist, 2012). Recently, Neumann and Village (2012) presented a framework for integrating HF into multiple levels of early production systems design, and they suggested the need for tools to assist with this integration.

HF specialists (HFS) have a wide range of tools and techniques (David, 2005; Neumann et al., 2006; Garg & Kapellusch, 2009, Wells et al., 2012); however, there are several problems with HF tools that limit their application in engineering. First, most HF tools focus on reducing injury risk or system errors (Marhavilas et al., 2011) rather than improving operator performance. As Zhang et al. (2008) stated, engineers want to improve the failure tolerance of operators for reliability and accuracy. Current injury-based HF tools do not address these goals. Along with the injury focus, HF tools also tend to target the worker–workstation level instead of the system level. Second, HF tools and methodologies often lack a clear link to company strategies (Eklund, 1997; Dul & Neumann, 2009). HF methods have been developed largely as “expert” methods for use by HFS, with ambiguous process ownership and control (Eklund, 1997). Third, most HF tools are ill-equipped to predict design problems, where more cost-effective changes can be applied. A limited number of digital human modeling and virtual human simulation tools (like 3D SSPP or EAI Jack, ErgoMan) are being used in large companies, especially automotive (Rajan et al., 1999; Gilad & Elnekave, 2006; Duffy, 2007; Lamkull et al., 2009; Yang et al., 2009; Hu et al., 2011; Otto & Scholl, 2011). However, it is questionable whether these tools are accessible, cost-effective, and practical in manufacturing environments (Perez & Neumann, in press) and whether they provide meaningful design recommendations to engineers (Kaljun & Dolsak, 2012).

Govindaraju et al. (2001) stated that unless HFS evaluate the effects of their recommendations on production factors, such as production volume, rate, product design, etc., they will have little or no impact on engineering and systems design. HFS have failed to provide useful models, checklists, methodologies, and tools to help designers (Clegg et al., 1996; Wulff et al., 1999) and that improved proactive HF methods and tools are needed that are appropriate for production engineers (Wells et al., 2007; Falck et al., 2010; Ma et al., 2010; Teperi & Leppanen, 2011).

This article presents a demonstration case study of how five engineering design tools were adapted for HF and incorporated into several design stages in a large electronics organization with the following objectives:

- to describe the process for adapting five design tools to include HF and illustrate how they were integrated into the production design process;
- to briefly describe the need for, and value of, the adapted tools; and
- to provide advice and recommendations for practitioners regarding features of effective HF tools and ways to integrate HF into engineering design tools based on the results of this study.

# METHODS

## Description of Industry–Research Collaboration

This article is based on a multi-year collaboration between HF and engineering researchers in industrial engineering at Ryerson University and HFS and engineers in a large electronics manufacturer. The collaboration goal was to improve the company's capability to integrate HF into its engineering design processes. The collaboration was supported both from the Director of Engineering and the Director of Occupational Health and Safety, who manages the HFS. Since 75% of the assembly tasks are done manually, there was recognition from senior management that HF, specifically minimizing worker fatigue, can help with their goal of reducing assembly defects (Village et al., 2014).

The HF researchers guided the industry HFS in negotiating the design process, identifying the need for HF tools, and integrating these tools into the design process in a way that would be sustainable for the HFS in the company. However, to maintain participant confidentiality, HFS is used throughout this document to refer to the researcher–industry team. It will not be specified whether the HFS was a researcher or industry specialist, or whether they acted alone or with others.

An action research (AR) approach was used, where researchers were embedded in the organization and together took action to adapt or develop methods, tools, and techniques for integrating HF into design processes; they then reflected and learned from their actions (Neumann et al., 2012). The AR collaboration, which involves ongoing cycles of planning, acting, observing, reflecting, and re-planning, ensures that the action (or tools) are appropriate and sustainable for the organization and that learning about how to adapt tools for HF is transferred to the organization participants.

## Context of the Organization

The context of the organization is important background. The site, called "New Product Realization" (NPR), has a goal of developing an assembly process for each new product that is capable of meeting quality, delivery, and cost targets. The focus is on the design for manufacturing and assembly of new products and not on the worker–workstation or work organization interface, which is uniquely determined at each outsourcing manufacturing site. At NPR, engineers attempt to identify and remedy those factors that make it difficult and cumbersome for a worker to assemble a product, which could include problems with parts, tolerances, tooling, suppliers, and clearances. Problems, such as components not fitting or clearances being too tight for manual assembly, if undetected, could become massive issues in terms of cost, delivery, and quality when the product is launched for mass production at other locations. Workers at the NPR site never reach mass production volume or speed; instead, they produce small batches of product in an iterative design optimization cycle with a close check on quality of every part.

It is also important context to explain that prior to the collaboration, the HFS within the NPR site were not directly involved in design of the assembly process. They were organizationally disconnected from engineering, within an occupational health and safety department, and most of their work was recommending workplace modifications in response to incidents of worker injury. Their recommendations were not communicated to engineering and therefore did not carry forward to subsequent assembly designs (Village, 2014). The overall goal of the collaboration, consistent with that of the HFS in the organization, was to find ways for the HFS to work proactively with engineers when designing the production assembly system.

## Data Collection

Over 3 years, researchers worked regularly with engineers and HFS in the organization using a variety of interaction methods, including meetings, interviews, workshops, training sessions, shop-floor assessments, analyses of collected findings, video recording assessments, expert reviews, presentations, conference calls, and e-mails. Diverse engineers and senior managers were engaged in the project when and where it was helpful to the initiative's progress. Field notes were taken during and following each interaction. Meetings and workshops were audio-recorded and transcribed. Artifacts from within the organization were another data source and included product specifications, manufacturing and assembly plans, work instructions, project charters, FMEA scoring records, process flow diagrams, prototype fixtures, and mock-up workstations.

## Data Analysis

All notes and transcript data were open-coded in NVivo software (QSR International 2010, Burlington, MA) for qualitative analysis, per early stages of a grounded theory approach (Strauss & Corbin, 1990). The qualitative data were sorted and reviewed for this article from two broad analysis categories: "aligning with engineering and business process improvement programs" and "application and uptake of HF." The data were analyzed to trace the steps in the development and implementation of each tool. The constant comparison method was used to compare the different tools on factors, such as beneficial features, ease of implementation, and level of influence. Quotes taken directly from transcriptions of participant meetings and workshops were included where helpful. For this report, only data related to development of HF tools are presented.

## RESULTS

While working in vivo with the organization toward the collaboration goal of integrating HF into the design process, it became apparent that the HFS needed tools to communicate, quantify, and document HF aspects of design. As the collaboration proceeded, the HFS team actively increased their understanding of the in-house design process, identified the need for HF-oriented tools at different stages of the design process, adapted tools currently used in the organization to include HF, and used the HF tools to set targets for subsequent product builds, thus integrating HF tools into the design process. This results section will highlight this overall process for adapting tools, briefly describe the development process and value for each of the five tools, and summarize tool features critical for the design engineers in this organization.

### Process of Adapting and Integrating HF into Engineering Design Tools

The approach to tool development was not structured and linear. The researchers did not have preconceived ideas of tools that needed adapting or the steps for achieving this. As the collaboration proceeded, the need for HF tools, or adaptation of tools for HF, became apparent to both engineers and HFS. Engineers suggested to HFS that they

> develop a tool, use the tool, get a measure, show results, interpret, set a target/goal then talk about process (who owns it, does it, when and where)."

They were also told that

> HF would be measured by the product being manufacturable—using process capability measures (e.g., tracking defects)

While each tool had a unique development process, the overall process of adapting and integrating HF-related tools appeared to involve four generic phases, which are described next.

(1) *HFS needed to understand intimately the steps and language of the design process*. To understand the design process, HFS needed to participate in meetings when new products were being discussed, meet with vendors when fixtures were being developed, and participate on the shop floor when the first assemblies were built. They needed to understand intimately the issues faced by the engineers who are building the assembly system and how such issues are resolved. They also needed the terminology and language of in-house design steps and technical aspects of materials, parts, and processes to participate with engineers. The experienced assembly

engineers in the organization had knowledge of operator capabilities and limitations, but their terminology (i.e., precision versus risk factor) and end goal (i.e., ease of assembly versus minimizing injury), compared to HFS in this organization, were different. The HFS documented the key stages of the design process, as shown in Figure 1, and identified the engineering groups involved and the decision gates and timing for each step. Product design is shown in dotted lines, as it is provided from other company locations and departments and seen as an input to this part of the design process. Mechanical engineers receive product drawings; they then plan how best to manufacture the product parts and convert product drawings to working designs (NPR stage). At this stage, quality engineers conduct a product FMEA to identify and control potential quality issues prior to building parts. At the design for manufacturing and assembly stage, process engineers develop the sequence of tasks for assembly. A process FMEA (pFMEA) is then conducted to control potential quality problems related to the assembly process with various engineers (production, test, quality, manufacturing, and suppliers). If it is determined that an assembly step cannot be performed manually, then tooling and fixtures are designed (to hold or help assemble components) in the next stage by another group of engineers. At the prototype build stage, product-focused engineers work closely with quality and manufacturing engineers as well as workers to detect problems with early assembly. During the process optimization stage, adjustments are made to improve the assembly for mass production. In product launch, the assembly system is sent to another facility for mass production. Several new products are realized annually; the cycle takes approximately 1 year.

(2) *HFS needed to understand the important metrics driving business performance*. The metrics that drive engineers must be understood by HFS to ensure that HF becomes a means to support or realize the strategic goals of the organization. The HFS interviewed quality specialists to understand what they measure (key performance indicators [KPIs]) and how. Senior management was also interviewed to understand critical strategies and goals in the organization. HFS then needed to articulate and communicate ways that HF can help, rather than hinder, engineers in attaining business goals. For example, instead of a focus on reducing injury, HFS would suggest that reducing the force needed to connect two parts would result in less worker fatigue and improved worker consistency and quality. In early discussions about how to integrate HF into their design process, one engineering manager during an interview stated:

> we need to target manufacturing managers to see how our (HF) measures can make their job better—how can it be red/green for them—find a correlation based on their reporting and have them want to measure it—tie it to quality especially.

By learning the important quality metrics, HFS shifted their focus to look for ways to improve assembly quality, for example, by making the assembly task easy and comfortable for the worker to perform, by reducing worker fatigue, and by ensuring workers could detect quality problems.

(3) *HFS needed to understand tools currently used in engineering to meet business goals*. Tools used by engineering designers, such as FMEA, are not typically taught in HF educational programs. A working knowledge of tools gained by practical application alongside engineers was needed to realize how tools can be adapted to incorporate HF. The HFS in the organization worked alongside engineers to learn the tools used in the design process. They attended FMEA meetings, kaizen activities on the shop floor, hoishins, and gemba walks with senior management. The HFS also took a 6-day course in six sigma to help improve understanding of engineering tools.

(4) *In participation with engineers, the HFS needed to adapt current tools, or develop unique tools, that fit the design process and that provide important metrics for business performance*. With knowledge from the first three phases, the HFS were positioned to work alongside


**FIGURE 1** **Assembly design process.**

engineers from the various areas to adapt design tools to include HF. Figure 2 shows the various tools adapted for HF integration in the assembly design process: HF-pFMEA, HF design for assembly (HF-DFA), HF design for fixtures (HF-DFF), workstation efficiency evaluator (WEE), and HF kaizens. The HF-pFMEA, HF-DFF, and HF kaizens were direct adaptations of tools already used in the design process. The HF-DFA was developed with engineers as a unique tool but based on a known DFA concept and integrated into a new DFA process in the organization. The WEE is also a unique tool purposely designed to fill the need for a simple and quick workstation layout tool that can be used at the CAD design stage (Greig et al., 2011, 2013). At product launch, HF lessons learned are documented with other manufacturing lessons learned in a standardized engineering reporting structure for feedback during the next product launch.



## Descriptions of Engineering Design Tools Adapted for HF

In this section, the tools are briefly described with an emphasis on their need and process of adaptation or development and the value of the tool to the design process. The tools are company prototypes, customized for the type of assembly and design process within the case study organization. References are provided for those wanting to review the tools in more detail to customize them for other applications (Village, 2014). Table 1 summarizes, for each tool, the purpose, inputs, outputs, and tool application in the case study. A brief description of each follows.

### HF-pFMEA

#### Tool Need and Process of Adaptation

In the design for manufacturing and assembly stage, engineering and quality teams in the organization perform pFMEAs to minimize quality problems. The HFS attended several meetings to learn the FMEA process and observed that many assembly tasks with quality issues also have HF implications. When the HFS asked engineers, for example, how connector force was determined, they responded that it had to do with part tolerance, not worker capabilities. The HFS realized they could contribute a different perspective to the FMEA team.

Engineers suggested the HFS develop an HF-FMEA with a similar scoring system to the quality FMEA. Various scoring options were discussed and evaluated among HFS on current assembly lines and via videotape of assembly tasks. The HFS also compared scores for inter-rater reliability to further improve and refine the descriptors. A challenge faced by HFS was to determine a scoring system that would include not only physical implications of assembly tasks (such as force), but also potential for operator error or challenges with detection of a quality problem. As a start, the HF-pFMEA, containing only physical risk factors, was incorporated into a template and embedded in FMEA software that was being upgraded within the company. HFS subsequently attended pFMEA meetings for new products, performed HF-pFMEA scoring for manual assembly tasks, and, collaboratively with the engineering team, identified solutions where scores were high (Village et al., 2011). High scores are traced in the FMEA software system and must be resolved with alterations to parts, materials, or fixtures before moving to the prototype stage.

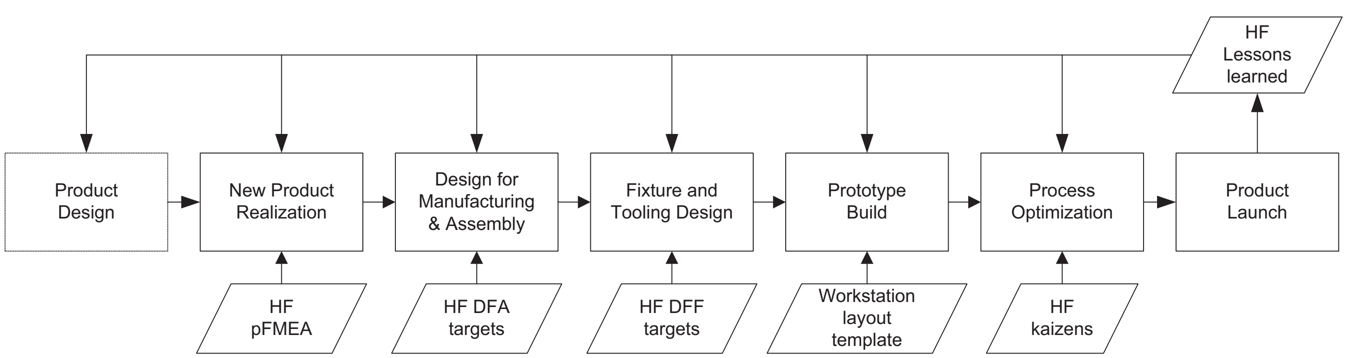


**FIGURE 2** Integration of tools adapted for HF in the design process.

**TABLE 1** **Description of HF purpose, inputs, outputs, and tool application in case study**

| Tool | HF purpose | Inputs | Outputs | Tool application |
|---|---|---|---|---|
| HF-pFMEA | • To detect risks that predispose worker failure (i.e., injury, fatigue, or assembly difficulty) prior to manufacture of parts | • 3D product drawings initially<br>• Possibly prototype parts<br>• Video observations at first build | • Risk priority number (RPN) per task as product of severity, occurrence, and detection of risk | • HFS scores HF-pFMEA at meetings with engineers<br>• Tasks with high RPNs are improved by engineers and HFS prior to manufacture |
| HF-DFA | • To ensure tasks meet HF and assemble-ability targets at first build<br>• To prioritize and monitor tasks for improvement | • Observation or videotape of first build using prototype parts | • HF-DFA score (0–2) for 22 items and overall score (maximum 44) | • HFS scores each task<br>• Any "2" requires improvement<br>• Tasks with highest overall scores require engineering improvement<br>• Final sign-off by HFS |
| HF-DFF | • To provide HF fixture[a] design targets prior to design and manufacture to improve human performance | • Fixture and tooling requirements<br>• Fixture design review<br>• Prototype build<br>• Qualification | • HF-DFF score (0–2) for 12 items and overall score (maximum 24) | • HFS scores fixtures at each input stage<br>• Any "2" requires redesign<br>• Final sign-off by HFS |
| WEE | • To provide timing and line balance of tasks, as well as optimal layout of workstation parts and equipment prior to build | • Element descriptions<br>• CAD drawing of layout<br>• *x*-, *y*-, and *z*-coordinates of hand locations from drawing | • Time per element and cycle<br>• Reach zones exceeded<br>• Shoulder load (acute and cumulative) and recovery | • Cycle time for engineers for task and process optimization<br>• HFS evaluates layout at drawing stage to optimize |
| HF kaizens | • To engage operators at first build to optimize HF | • Operators' concerns (verbal and written) and quality data during first build | • Recorded suggestions for improvement discussed with supervisors, engineers HFS, and health and safety | • HFS participates in kaizens; HF is considered alongside other quality and engineering concerns |
| Lessons learned | • To document HF lessons learned for subsequent products | • Scores, observations, concerns, and variances noted | • Documentation in standard engineering reporting structure | • HF lessons learned are fed back to each appropriate design stage for subsequent builds by HFS |

[a]A fixture is a device used to secure a work piece, generally while a machine or tool performs an assembly task.



### *Value of Tool*

An HF-FMEA tool with similar scoring, and an HF template in the software, helped facilitate ongoing buy-in and use by engineers. The tool was a means of early identification of potential HF issues at the stage of part design. In this case study, it promoted discussion about HF implications with engineers and, with the software, provided a means of tracking HF issues and solutions.

## *HF-DFA*

### *Tool Need and Process of Adaptation*

The HFS worked with engineers through a full assembly production design cycle of a new product to help identify and improve tasks with respect to ease of assembly. However, as the researcher notes below indicate, the HFS recognized that some sort of tool was needed to make their involvement sustainable:

> 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 we can't just indicate problems–we need tools for sustainable processes.

To satisfy this need, the HFS developed an HF-DFA tool, loosely based on the DFA by Boothroyd et al. (2001), to evaluate the ease of manual assembly tasks and to prioritize tasks for improvement. The tool included 22 items known from the scientific literature and experience of engineers and HFS to contribute to concerns related to HF, ease of assembly, quality, and speed of assembly in hand-intensive assembly tasks (Village, 2014). A simple 0–2 scoring system was devised, where "0" represents an easy assembly, "1" moderate ease, and "2" a difficult assembly, for a maximum score of 44.

To demonstrate the tool, scores for the 22 assembly steps were collected from an existent assembly process and presented to engineers and senior directors; tasks with higher HF-DFA scores corresponded to tasks recognized both by workers and engineers as needing improvement. Two participatory workshops were then conducted with 12 engineers to further refine and improve the HF-DFA items and the item wording and interpretation. Engineers scored videotaped tasks, and those scores were compared for consistency and interpretation problems. Engineers responded favorably to the tool, as noted by the following quote:

> this highlights to me something that I hadn't been aware of, so it's great–we sort of look at the line but this helps us see things precisely–put numbers to it–doesn't matter what they are and makes engineers see things differently.

This quote reinforces that these engineers liked having a tool with quantifiable outputs to help them compare tasks and indicate areas for improvement. The HF-DFA has since become a "controlled document" owned by engineering, and its score is one of four targets (along with quality defects, fixture cost, and scrap) that engineers must achieve prior to a new product launch. The HFS scores the tasks, and any scoring of a "2" must be improved by engineers. Tasks with high total scores must be continuously improved during the various prototype stages.

### Value of Tool

The unique HF-DFA tool with a simple and quick scoring system combines HF considerations with quality and production concerns and promotes discussion about the combined effects in design of tasks in this company. The tool has been used within the company by numerous engineers and HFS to identify tasks needing improvement and to re-score tasks after improvements. The face validity and simple scoring of the tool facilitated integration into the design process and its use as an HF "metric" alongside other engineering metrics.

## HF-DFF Targets

### Tool Need and Process of Adaptation

Fixtures in the assembly design process may be developed in-house or by outside vendors. Since fixtures operate at the interface between workers and equipment, their design can influence the forces, postures, and ease of assembly, which in turn influence production speed and quality. The engineering team responsible for fixtures was standardizing their fixture design process and suggested that the HFS include some HF guidelines. HFS assessed fixture designs on an operational assembly line and consulted with workers to identify 28 design concerns. They also discussed with engineers the quality and production implications of those concerns. A 2-hour participatory workshop was held with nine design engineers to "translate" the HF concerns into design guidelines with appropriate wording for designers; that is, the item was worded in engineering terminology (i.e., "remove obstructions for clear access for device insertion") rather than HF terminology (i.e., "minimize awkward wrist bending").

The final HF-DFF tool contains 12 items and, similarly to the HF-DFA, had a scoring system from "0" (low HF risk) to "2" (high HF risk). More information about the HF-DFF can be found in Village et al. (2012) and Village (2014). It was also incorporated into a controlled engineering document with HF targets established within the DFF process. The HFS provided training in the HF-DFF guidelines to internal and external engineers who designed and bid on fixture development. As with the HF-DFA, the HFS scores fixture designs, and any "2" must be re-engineered to reduce the score.

### Tool Value

The combination of the HF-DFF tool and integration of the tool in the standardized DFF process ensures that the HFS attends meetings with vendors, scores all fixture designs and prototypes, and signs off at the fixture design, prototype, and final construction phases. Since fixtures move with the product to production facilities worldwide, careful fixture design ensures both product quality and improved HF for many workers.

## WEE

### Tool Need and Process of Adaptation

Development of the unique WEE tool arose from a perceived need from HFS for a tool to establish and evaluate workstation layouts at CAD drawing stages of assembly design; more detail of WEE development was provided in Greig et al (2013). Its initial version, based on element descriptions, the CAD workstation drawing and hand locations in the *x*-, *y*-. and *z*-axes for each element (e.g., reach for part) were developed to track hand motion. Later versions included models for shoulder load and recovery time. The engineering group became especially interested in the tool with the addition of Methods-Time Measurement (MTM) timing information to predict task and cycle times and to assist with line balancing and production cost estimation before distributing tasks to assembly workstations.

### Tool Value

The tool demonstrated to engineers that minimizing excessive reaches, due to parts layout, fixtures, and assembly steps, not only poses risk of injury to workers but increases task time (seen as motion waste). The tool has been used by HFS in several product cycles to predict cycle time for engineers and also to indicate shoulder loads and reach zones. Targets for reach zones and for continuous improvement of workstation layout have recently been added to increase usability of the tool.

## HF Kaizens

### Tool Need and Process of Adaptation

Kaizen is translated from the Japanese to imply incremental continuous improvement (Manos, 2007; Stone, 2010). It is a team activity (not a "tool" per se), the purpose of which is to turn "lean thinking" into actions to eliminate waste (or non-value added activities) within the work process, job design, or equipment. During the case study, the organization had been increasing its use of Toyota Production System methodologies and continuous improvement. More managers and workers were attending training courses and initiating events, such as kaizens, in the process optimization stage to engage workers in optimizing quality and performance on the assembly line. When an injury occurred on the line and the HFS was called to investigate and assess it, the floor supervisor recommended initiating a kaizen to involve workers in recommended improvements. Results of the initial HF kaizen were distributed to other engineers and floor managers, increasing their awareness of the overlap between optimizing HF, quality, and production. After seeing the benefit of incorporating HF into their kaizens, the engineers and floor supervisors now include the HFS as regular participants.

In the case study organization, the kaizen is conducted in two stages. When operators first assemble small batches of devices, they note concerns with workstation layout, fixtures, or parts on sticky notes and post these above their workstations. For example, one kaizen was initiated when workers had difficulty clearly seeing a small part being assembled. The floor supervisor assembles the concerns onto flip charts in the immediate assembly area. Concerns often have both an HF component (such as visual difficulty) and a quality component (such as defects if the part is missed or inserted improperly). A kaizen meeting is then conducted, where workers discuss their concerns with engineers, HFS, and managers, and possible solutions are identified–much like participatory ergonomics. Solutions are documented and implemented by floor supervisors and engineers and once again evaluated by workers in ongoing continuous improvement efforts. In the example of difficulty seeing a small part, a magnifying glass was designed into the fixture to improve vision.

### Tool Value

HF kaizens are a mechanism for HF issues to be discussed alongside quality and production problems in a participatory way with workers, engineers, and HFS to find the most effective solutions before the final assembly design is launched to outsourcing countries.

### *Features of HF Tools Found to Be Effective for Proactive Design*

The previous section illustrated that the selection of tools to adapt, and the process for adapting them for HF, was opportunistic, based on the design process in the organization, processes in place, and the needs of the engineers. Some tools, such as the HF-DFA and HF-DFF, are integrated into the design process with measurable metrics that engineers continue to be held accountable for meeting. The HF-FMEA tool was used for subsequent product builds, but a change in organizational direction later resulted in the entire FMEA program being canceled toward the end of the collaboration. The HF kaizens and the WEE tool are initiated on an "as needed" basis, rather than being locked into the design process. Based on what engineers shared with researchers over the 3 years of the tools' developments, a list of 12 recommended features (listed below) was compiled of an effective HF tool for use in proactive production systems design. Tool features reflect the outcome of the tool that indicates how they fit in the design process, the usability features, and the process of development. Each feature was substantiated with qualitative data from the case study. Furthermore, following analysis of the data to review these features, a verification meeting was held with the senior director of engineering and several manufacturing engineers. The present case study has demonstrated that if tools contain the following features, they are more likely to be locked into the design process by senior management:

(1) can indicate HF issues at early design stages (versus after problems arise);
(2) fits with engineering processes, language, and tools;
(3) directly addresses operational/business goals and influences key metrics;
(4) are quantitative (e.g., yields a score, rating, KPI, threshold, or target) and can demonstrate change (facilitate action);
(5) leads to best practices and benchmarking;
(6) provides lessons learned;
(7) fits expectations with respect to level of detail, engineering workload, and ability to meet key milestones;
(8) has good tool utility (visual, quick, easy, nimble);
(9) sensitizes engineers to HF problems—allows them to see differently;
(10) has been developed and validated with in-house expert input and participation;
(11) has permanence (versus one-off type of assessment) and is not person dependent; and
(12) is thorough and well documented (not observation or verbal).

Many of the features in the list above reflect the outcomes or "fit" between the HF tool and existing engineering design processes, tools, language, and strategic business goals. As discussed in the section entitled "Process of Adapting and Integrating HF into Engineering Design Tools," the HFS needed to spend sufficient time within the engineering group to know not only what tools to adapt but how to ensure they fit the expectations and needs of the engineering groups. Introducing HF into engineering design tools was easier for engineers in this case study than expecting them to learn HF tools. While the tools and their adaptations may be different in other organizations with different design processes, the ways HFS worked with engineers to adapt the tools and the features of effective tools may be helpful for others in a similar environment.

## DISCUSSION

This article has demonstrated the process of adapting five engineering design tools to include HF considerations and has illustrated how the tools have become integrated into a company's production systems design process. The AR methodology facilitated the implementation and close experimentation with HF tools in vivo while also actively researching and learning in a real life environment—an approach advocated and used by other researchers (Zink et al., 2008; Carayon, 2010; Wilson, 2012). The resulting tools were integrated into the organization's assembly design process, largely because HF was incorporated into familiar tools, and because they used metrics related to the business goals of the company. Tools that address HF proactively (i.e., before injuries occur) can improve human aspects of the assembly design for thousands of workers in the organization in multiple countries. The benefits of adapting engineering design tools are that engineers are already using them, they are business and performance oriented, they get the attention of senior management, and they lead to a "pull" for HF into engineering as a resource rather than having HF as a separate group trying to "push" their way into the design process.

Adapting engineering design tools achieves better integration with the design methodology of the organization and the specific production system (Neumann et al., 2009; Neumann & Village, 2012).

A few other researchers have also reported success in integrating HF into engineering design tools in healthcare (Carayon et al., 2007, 2010) and manufacturing (Gawron et al., 2006; Zink et al., 2008; Falck & Rosenqvist, 2012). Sen and Yeow (2003) also developed unique company-specific tools for electronics manufacturing in a participatory way with expert teams. They reported that their approach, compared to other HF methods, reduced effort and resources, was easier and more flexible to apply, and was more accurate with lower cost and less need for expert involvement. Participatory adaptation of tools, aligned with business metrics and goals, may be one way HF can demonstrate its value to the main stakeholders of systems design (Dul & Neumann, 2009), an issue Dul et al. (2012) suggested the HF community has failed at, even though the present definition of HF implies a systems approach that is design driven and focuses on improved performance and well-being (International Ergonomics Association [IEA], 2013).

The results in the "Descriptions of Engineering Design Tools Adapted for HF" section reveal that successful implementation is more than simply adapting or adopting a tool. Each of the tools in the case study followed a different development course, and some became enforceable targets more readily than others. While support from the senior director of engineering helped provide initial access to the engineering department, the buy-in from each engineering group was obtained when their needs were understood, and HF was adapted to help them achieve their design goals. This information was included to encourage others to use a participatory approach to develop and adapt tools. To the best knowledge of the authors, sharing results of such a process is uncommon in HF literature, and much can be gained by this qualitative analysis of "how" tools were adapted and integrated. Perhaps lack of attention to the process of introducing HF knowledge early in production is one reason so many efforts have not brought about change (Jensen, 2002). Others are also encouraged to report more about the "how" of development processes.

The results of this study suggest that HF and ergonomics education programs would benefit from more training in engineering design tools, techniques, and processes. Recommendations have been made for more systems design knowledge, especially of trade-offs and constraints (Campbell, 1996). Wells et al. (2007) suggested that knowledge of engineering tools will help HFS practitioners understand design decisions better so they can propose strategies without negative side-effects. Strasser and Zink (2007) suggested that increased training in engineering is essential for HFS to have the self-confidence to challenge systems-ergonomics requirements. In a case study without such training, Neumann et al. (2009) observed that HFS lacked the knowledge and language to engage meaningfully with the engineering design team, and as a result, the uptake of HF among engineers was limited. In the present case, the co-development of tools seemed to help bridge this gap.

The tools reported here were all developed within a single case study in an NPR site within the electronics sector, which may limit their applicability to other organizations and sectors. While being cognizant of human error and cognitive demands of the assembly tasks, the tools predominantly focus on physical HF aspects. The need for more research and development of tools that address such issues as task complexity and error detection is recognized. The influence or outcome of the tools on workers in the final production lines could not be evaluated, since they are launched in other countries. Although the tools promoted a reduction in manual force and awkward postures and improved visual detection of problems, ease of handling, and assembly of parts and tooling, it is not known if the effect resulted in overall work intensification or increased line speed. These types of outcomes, as well as the influence of design-level HF tools compared with other aspects, such as work organization and job design, require further research and evaluation.

It is suggested that the contribution from this case is not the tools per se, but the lessons learned about the process of adapting internal engineering tools and customizing them to one's design process and context. The 12 recommended features of an effective HF tool for productions systems design may be useful to other practitioners doing similar work. The engineers worked with in this study believed it was critical that tools be quantifiable, provide a target or threshold, and drive improvement. The managers and engineers in this case study were willing to start with an estimated score or target, use the tool, drive the change, and re-evaluate the target. Others have also recommended analysis tools with an intensive focus on hard factors and figures (Falck & Rosenqvist, 2012) that are specific and quantifiable (Wulff et al., 1999). In the discussion of HF tools by Wulff et al. (1999), the authors suggested that engineers like tools to show and communicate to others what constitutes "good design." Numbers make it easier to establish whether a requirement is being fulfilled.

It was also essential that the tool "fit" with their design process, time frame, level of detail needed, and engineering workload. A feature was included that tool utility should include being visual, quick, easy, and nimble to use. Finally, tools should sensitize engineers to problems and help them see an assembly task from different perspectives. In the present case study, an HFS was available to the engineers to use and interpret the adapted tools. The tool was a trigger to initiate a conversation about HF implications in the design process, providing an opportunity for the HFS and engineer to collaboratively develop a solution. It cannot be assumed, however, that these adapted tools would initiate HF discussions in organizations that do not have an HFS. Use of the tools without an HFS requires further study and evaluation.

In this case study, there were no HF tools developed to influence product design (the first stage of design in Figure 1). Eklund (1999) showed that 60%–70% of ergonomic impact is affected by decisions made at the product design stage and 30%–40% in the manufacturing process. While senior directors in the present case study acknowledged that many assembly difficulties arose from decisions made during product design, the manufacturing and assembly team reported having little success communicating these concerns or influencing product design proactively. As others have found, product design engineers are often removed physically from manufacturing and do not realize the outcomes of their decisions on assembly workers (Wulff et al., 1999; Neumann et al., 2009), and reaching these designers appears to be difficult. Development of effective tools that include HF considerations and could communicate HF-related design concerns to product design groups remains an area in need of more research.

The main limitation of the tools adapted in this case study is the lack of "testing" or scientific "validation." Some HF issues may be overlooked in a given tool, a different scoring or weighting system may work better, and there has been very limited formal repeatability or reliability testing performed. Compared to the research-focused development process for most HF tools, this may be considered a weakness. However, the participatory development approach recommended here necessarily results in ad hoc tools customized to the local context, where there is neither demand nor resources for extensive validation. Practitioners and others are interested in these "practice-focused" HF tools, even if not scientifically validated, since tools can then stimulate and initiate further customization and research (Buckle, 2011). Rather than having strict validated threshold limit values, most engineering tools used in systems design are more about continuous improvement and problem solving (Dul et al., 2012). Consistent with the design emphasis and engineering approach, perhaps HF should aim more at creating novel possibilities for action (Nathaneal & Marmaras, 2012) and taking a problem-solving stance (Broberg, 2007) with methodologies and structures for continuous improvement processes (Eklund, 1997; Zink et al., 2008).

## CONCLUSIONS

Five engineering design tools were adapted to include HF considerations and were integrated at each stage of assembly design in an electronics manufacturing company. Engineers and management responded positively to the tools because they were designed to help improve assembly design and achieve business goals. Several of the HF tools became required targets within the design process, ensuring that HF considerations are built into all future design processes. Adapting engineering tools, rather than using HF tools, required a shift for HFS, who needed to expand their knowledge of engineering processes, tools, techniques, language, metrics, and goals. Having the HF tools "owned" by engineering, however, makes the HFS a critical resource. It is hoped that the lessons learned in this case study inspires other HFS to move beyond current HF injury-based tools and the discussion of risk factors. To be effective in an engineering design environment, it is suggested that HFS increase their understanding of the design process in the organization, learn which tools are commonly used in engineering, focus on important metrics for the business goals, and incorporate HF into engineering-based tools and practices in their organizations.

## CONFLICT OF INTEREST

The authors declare no conflict of interest.

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