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INDICATORS FOR MANAGING HUMAN CENTRED MANUFACTURING

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ABSTRACT

Establishing indicators for managing human factors (HF) aspects in the design of production systems remains a challenge. We address the problem in two dimensions – firstly, what aspects of HF are to be considered, and secondly, where in the development process HF is to be measured. In these dimensions a large number of HF metrics are possible in the perceptual, cognitive, physical and psychosocial domains of HF. The relevance of these measures to injury, productivity, quality and organizational strategy continue to be poorly understood. From this perspective we make propositions on the need for: 1) strategic HF metrics selection, 2) metrics application throughout the development process, 3) predictive 'virtual' HF metrics approaches, 4) metrics based design guidelines, 5) connecting metrics with design choices and strategies, 6) integrating HF metrics within existing approaches, 7) continuous improvement of the metrics system, and 8) the need to evaluate metrics system quality.

Keywords: Indicators, ergonomics, evaluation.

1 INTRODUCTION

Operational excellence in manufacturing hinges on an optimal fit between the technical system design and the capabilities of the human operators of the system. Lack of attention to Human Factors (HF) has contributed to poor productivity, poor quality, compromised implementations of new technologies or processes, and to fatigue and injuries among operators. Estimates of the cost of work-related injuries are on par with the costs of all cancers combined (Leigh 2011), with musculoskeletal disorders (MSDs) posing the vast majority of incidents. Productivity and quality losses are usually many more times the direct costs related to injury – particularly if presenteeism losses are included (Rose *et al.* in press). If these losses, caused by flaws in the design of the production system, are to be controlled then it becomes necessary to establish indicators which can support decision making among design teams and managers responsible for the development and management of operations. This view hinges on the idea that 'If you don't measure it, you can't manage it".

This discussion paper contributes towards a framework to help facilitate the development of indicators to support the design and management of more 'Human Centered' Production Systems (HCPS) capable of providing sustainably high performance. Towards this aim, we draw on Melnyk *et al.* (2004) three level conceptualization of metrics: the individual measures or metrics themselves; metric sets which are used to guide and evaluate an individual's and team's work; and metric systems which refers to the entire approach to metrics in the organisation. Furthermore, as Melnyk *et al.*

(2004) point out, the metric system should help connect and guide operational activities to the strategic objectives of the firm. In both Engineering and HF disciplines, there has been little discussion of appropriate metrics systems for designing and managing HCPS. In this paper we limit our focus to the front line employees in production, and exclude the also important discussion of the working conditions and performances of other employees in the organization.

2 DIMENSIONS OF HF METRIC SYSTEMS

In this section, we adapt Melnyk *et al.* (2004) 'focus' (e.g. financial or operational) and 'tense' (e.g. predictive or outcome) dimensions of metrics to be the 'HF aspect of interest' and the 'Stage of Development' dimensions, respectively, which frame the selection and application of HF metrics in production organisations.

2.1 Dimension 1: HF Aspect of Interest

The span of HF is diverse and covers all aspects of human-system interactions. Drawing on classical machine-human interaction theory, one can classify four main components (or sub-dimensions) of the operator-manufacturing system interaction as being 1) perceptual, 2) cognitive, 3) physical, and 4) psychosocial – the last of which we include as a special case of cognitive aspects relating to the individuals experience of work and includes constructs related to 'stress' and 'support' at work (Grosse *et al.* submitted). In each of these components a broad range of measures and indicators are possible to describe and interpret the human interaction with the environment. Perceptual aspects of the human-environment interaction reflect how someone senses their surroundings, and can be quantified in terms of the 'signal strength'. For example, Lux can describe the ambient light levels, decibels measure the magnitude of sound exposure, while an olfactometer can establish the odour levels in the air. Perceptual factors influence performance since they determine what the individual understands about the work system's status. For example, poor light levels could negatively affect a worker's ability to detect quality defects whereas sound or vibration exposures could cause a significant distraction that reduces a person's ability to focus and mask possibly important performance cues that would indicate a task was correctly completed.

Cognitive demands of work tasks include mental workload and process complexity, as well as aspects like learning and forgetting. Classifying the level of task complexity, for example, allows determinations to be made about speed of work, the tendency for errors while under time pressure, and the average rate of learning for new operators in the system. Relevant metrics for cognitive demands could include short term memory system demands, long term memory system demands, conceptual or visuospatial manipulations demands, among other aspects. If any of these systems are overloaded, for example due to excessive line speeds causing a rushed pace or due perhaps to product complexity, then errors and quality deficits can be expected outcomes. The psychosocial conditions at work, are the product of both technical decisions like layout and production flow, which affects an operator's ability to communicate, as well as the human resource management approach such as job rotation or teamwork which also affects the interaction of operators in the system (Neumann *et al.* 2006). These factors are related to 'softer' elements of immediate concern to operations managers such as 'motivation', 'turnover', or 'job satisfaction' and have also been linked to a wide range of health outcomes for operators including MSDs (Moon and Sauter 1996).

Physical HF measures, the fourth component of HF, are arguably the most studied variables in occupational ergonomics. Physical loading information can be obtained at sub-cellular (e.g. ion exchange), cellular (e.g. muscle cell), tissue (e.g. muscle or tendon), or body-part (e.g. shoulder) level for all parts of the musculoskeletal system. Alternatively, loading information can be obtained at a more macro task-based level (e.g. torque reaction in nut running). Furthermore these exposure levels may be considered in terms of their instantaneous levels, their rates or patterns of change, or for their accumulated levels as a dose over a given time period – all of which may be associated with fatigue and subsequent performance decrements, or if the exposure is high, with increased levels of discomfort and MSDs. This is based on the underlying principle that mechanical loads exceeding the individual's capacity levels can cause tissue failure with consequent performance and health effects (National Research Council 2001). With hundreds of muscles in the body and many associated tissues supporting them, the potential number of descriptive metrics in this dimension is very large.

The brief summary above suggests that there are an enormous number of indicator metrics which might conceivably be applied in a production environment and which are associated with both performance and employee well being. The challenge for developing metrics to support HCPS is to identify those aspects that are most relevant to support design and management decision making in a timely and unambiguous way. This, we suggest, is a non-trivial issue which itself warrants research: How can a company identify a manageable HF metrics indicator set to secure operational excellence in production?

2.2 Dimension 2: Stage of the Development Process

For this metrics dimension we draw on a model of the development process, shown in figure 1, which has been adapted from previous studies and has been found generally valid in field research (Neumann *et al.* 2002; Neumann *et al.* 2006). The model groups the sequence of decisions and processes within the development process into strategic, product design, production system design, and operations; with the outcomes of the system being dependant on the operator. Senior management strategies guide the choices that are made in product design. At this stage HF aspects in production are already being determined: forces required in the assembly, part weights, product complexity, task precision, and reaches required for assembly are all being influenced by the design of the product (e.g. Neumann and Wells 2007). These HF considerations have implications for product quality, operator fatigue, and injury risk.

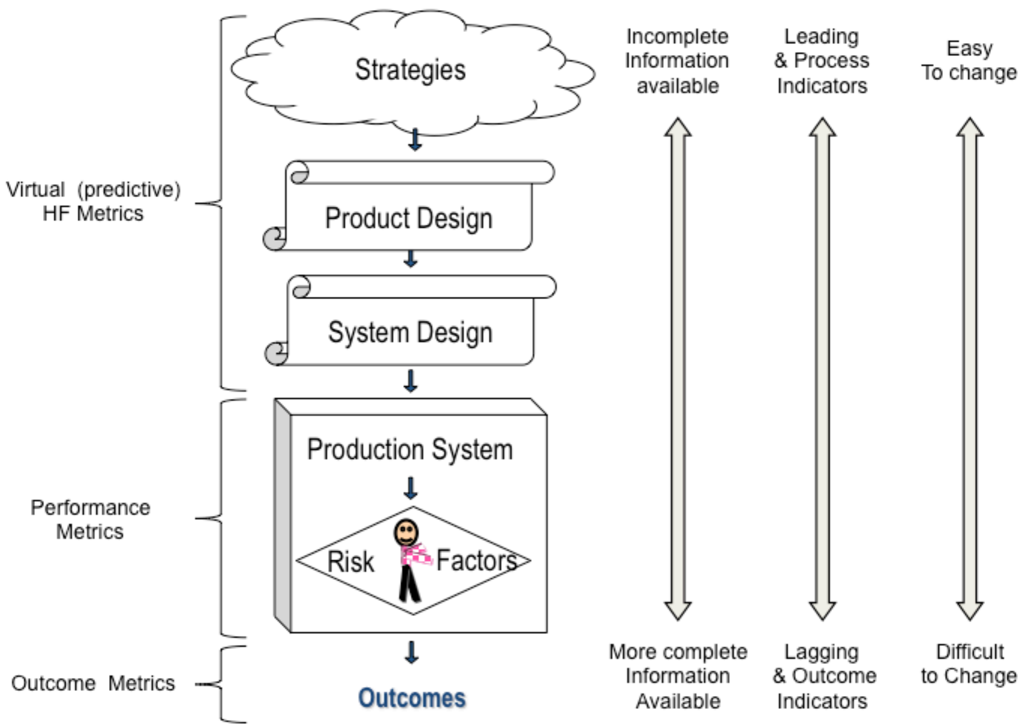

Figure 1: Model of the development system with reference to HF metrics issues

HF are further influenced in the design of the production system itself. Production system design choices, such as the flow approach, the material packaging and supply strategies, the conveyance system, the automation level, the workstation layout, and tool selection act to determine both the physical and psychosocial experience of the system operators (Neumann *et al.* 2002; Neumann *et al.* 2006). Finally, the management strategies applied in running the production system will also determine the pattern of work tasks for operators. Work scheduling, job rotation, and division of tasks will influence both the psychological and physical work pattern of the operator.

Using this model, we expand Melnyk *et al.* (2004) view of 'process' and 'outcome' indicators to include the possibility of a long chain of leading and lagging indicators which ultimately result in both human outcomes, such as increased competency, fatigue or injury; as well as system outcomes such as, quality levels, production volumes, and delivery precision. Both human outcomes (e.g. skill or injury) and system outcomes combine to provide the overall financial performance of the system. In this model as well we stretch Melnyk *et al.* (2004) notion of tense to include 'virtual' metrics indicators, which are predicting operational 'performance' metrics where the most complete HF information is available, and which in turn affects the outcome metrics which extend outside of the production system itself.

3 IMPLICATIONS FOR ESTABLISHING AN HF METRICS SYSTEM

In this section we reflect on the implications of the two dimensions of HF metrics as discussed above. We attempt to frame these insights into 'propositions' which can form the basis of future research and development work on this topic. We wish to emphasise that the aim of the metrics system for which the authors are striving, is not only to reduce injuries, but to secure sustainable high performance in production in ways that support the overall company strategy.

HF of INTEREST – Given the wide range of possible HF indicators, it is necessary to select some sub-set of indicators that might reasonably be used in the development process. This selection will depend on the nature of the work being planned; electronics assembly will have a different set of relevant HF from airplane assembly for example. One important issue, often misunderstood due to traditional relegation of HF aspects to health and safety concerns, is the linkage between HF and strategic goals like quality, productivity, and flexibility (Grosse *et al.* submitted). HF risk factors for quality, for example, may include most of the risk factors for injury, but will also include aspects that pose no particular hazard to health per se – such as poor perceptual characteristics. *Proposition 1: HF metrics must be carefully selected to be the most relevant to the particular operations in terms of injury risk, quality, and other strategic goals for the system.*

EARLIEST TIME POINT – It is a fundamental characteristic of design that the costs for making change in a design, in this case to improve the fit between the technical and human system elements, increases rapidly during the development process. These costs become maximal in the case of retrofitting an existing design in running production. Beyond just cost there are an increasing number of solution constraints as the design develops. If a better solution from an HF perspective is identified later in design it is more likely to be in conflict with design options chosen earlier in the process. Any team not attending to HF in their stage of development will likely cause problems for teams further down the development chain. There is therefore a need to consider HF aspects early and throughout the development process. *Proposition 2: The metric system should allow the identification and evaluation of potential HF issues at the earliest possible stage of development where the costs of change are lowest and solution constraints are minimal.*

PREDICTIVE TOOLS – Proposition 2 creates a challenge for predictive tools. In early design stages there is relatively little information about physical, cognitive and perceptual demands available. As the product and production system design develops, however, increasingly precise information becomes available until a full data set becomes, in principle, available in real production when, ironically, there is the least latitude to make improvements. The tools used to establish metrics in the design process will, of necessity, be predictive or 'virtual' in nature. 'Virtual' HF tools can provide measures and insights into the HF issues in a design before the design exists and there is a 'real' operator at risk to observe. While digital human models are perhaps the most widely studied form of VHF, we apply the term to a broad range of approaches which attempt to predict demands at the conceptual stages of design. These include checklists, virtual-reality, mixed-reality, and system simulations such as discrete event simulations (Perez and Neumann accepted). Given that most 'HF' tools have been developed for observation of existing systems this creates a challenge – and a research opportunity. *Proposition 3: Predictive tools are required to provide metrics at early design stages and, based on current development, these tools may need to be customised for the particular production context.*

DESIGN GUIDELINES vs METRICS – To bridge the gap between designers and operators, several authors have suggested the need for HF design guidelines or standards (e.g. Campbell 1996). Indeed, numerous HF standards exist, but it has been argued that engineers and designers either do not have access to the standards, do not know how to interpret the information, or have difficulty applying the information (Wulff *et al.* 1999). Under these circumstances the criteria is not applied. While some have suggested a guideline be supported by an HF professional, this might not be realistic for many companies. Instead we suggest that guidelines could be reinforced if framed within the context of a metric which could be used to hold the designer accountable for the extent to which they are meeting the HF specifications. *Proposition 4: Design guidelines should be applied in the form of a metric by which guideline compliance can be quantified and tracked.*

PERSPECTIVE CLASH – One challenge relating to the creation of design stage metrics and tools relates to the disconnect between the system design perspective of the engineering team and the task perspective of the system operators. Grosse *et al.* (submitted) have illustrated the perspective clash for the case of order picking systems: While engineers are focused on system elements like layout, storage assignments, routing, and work organization, the operator's HF related demands are linked to their tasks including: set-up, travel, search and pick. The technical choices of the engineering team do not have a one-to-one mapping onto a given HF aspect. For example the neck posture (adopted to assist in vision of a given product code) of an employee engaged in 'search' may depend on a combination of the racking used, the location of the code-slip, the size of the font, the lighting level, and the transport device of the operator (e.g. lift truck vs. cart). Similarly a given choice in racking may affect perceptual and physical aspects for several different tasks. *Proposition 5: Metrics and underlying design criteria need to be designed in ways that span the perspective clash between the technical design aspects and the HF relevant to performance.*

CONSIDER ADOPTION ISSUES – While one might think that there is a need for a specific set of tools to generate metrics throughout design, this might not be the most cost effective approach. Not only does this raise issues of cost and time to use the new tools, it also poses a problem of acceptance by engineers unfamiliar with these approaches. Instead, companies could consider adapting existing tools and approaches to include HF metrics alongside the traditional indicators. For example, the common 'Failure Mode Effects Analysis' (FMEA) approach can be adjusted to include specific HF aspects of relevance to the production context. These tools can lead to a more rapid uptake of HF in the design process because engineers are already familiar with them, and may also make it more difficult to ignore HF aspects that are inconvenient. We note here also that including the perspectives of the design team (the 'user' of any metric generating tool), in a participatory way, will likely help produce improved methods and acceptance of the resulting HF metrics approach. *Proposition 6: Adapting existing metrics approaches (tools) to include HF may be more effective than trying to develop and adopt separate methods.*

DYNAMIC METRICS SYSTEMS – Metrics systems need to be developed on an ongoing basis. One reason is that production strategies keep evolving, which implies that the way production operators work will also change and that new demands or different HF metrics will need to be applied to ensure the system will function as required. A second reason for the development is that the predictive 'virtual' tools used in earlier design stages are, of necessity, using incomplete information about the system. It is necessary therefore to have some means of ensuring that the 'predicted' HF metrics are accurately capturing the eventual actual demands in running production. *Proposition 7: The metrics system needs to have a mechanism to periodically check if the right HF are being captured, and to adapt the metrics prediction approach to better match the actual HF demands experienced in real production.*

METRICS SYSTEM OVERVIEW – How is a manager to know if they have a good approach to managing HF in their company? Compared to other issues, such as environmental aspects, there is no standard management system and no 'audit' type approach that would help the manager understand where improvement opportunities exist. In short, there is no approach to understanding the quality of a metrics system either with regards to other companies (benchmarking) or with regard to some idealised situation (auditing). This issue poses a challenge for both researchers and companies. *Proposition 8: There is a need for an approach to evaluating the completeness of a company's approach to managing and capitalising on HF aspects in their production system; an approach to scoring a metrics system's quality.*

4 DISCUSSION & CONCLUSIONS

This paper has attempted to understand the challenge of establishing metrics for HCPS design in the face of a very large number of possible HF metrics, which are influenced over a series of design stages which are themselves not understood in terms of the HF they affect. From this exercise 8 propositions have emerged regarding: 1) selection of appropriate HF metrics, 2) establishing metrics throughout the development process, 3) customising predictive 'virtual' HF metrics approaches, 4) implementing design guidelines in the form of metrics, 5) linking metrics to specific design choices and strategies, 6) adapting existing approaches rather than inventing new, separate metrics tools, 7) having an approach to improve and update the metrics system over time, and 8) the need for an approach to evaluating the overall quality of the metrics system. HF in manufacturing metrics systems has not been widely examined. While this paper contributes to this goal, it raises almost as many questions as it answers. There is considerable research required to understand what an optimal HF metrics system might be and how that system can help companies achieve sustainable competitive advantage in the pursuit of its strategic goals.

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