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Virtual Tools for Assessing Human and Organisational Factors in Production System Design

W. Patrick Neumann
Ryerson University, pneumann@ryerson.ca

Karolina Kazmierczak

Per Medbo
Chalmers University of Technology, per.medbo@chalmers.se

Faculty of Engineering, Architecture and Science

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Human Factors Engineering Lab, Ryerson University

www.ryerson.ca/hfe

W. Patrick Neumann, Karolina Kazmierczak And Per Medbo

For a more in-depth look on this subject, please see:

Kazmierczak, K., Neumann, W.P. and Winkel, J., 2007. A case study of serial-flow car disassembly: ergonomics, productivity, and potential system performance. Human Factors and Ergonomics in Manufacturing, 17(4): 331-351. DOI: 10.1002/hfm.20078

Neumann, W.P. and Medbo, P., 2009. Integrating human factors into discrete event simulations of parallel and serial flow strategies. Production Planning & Control, 20(1): 3-16. DOI: 10.1080/09537280802601444

Perez, J. and Neumann, W.P., 2010. The Use of Virtual Human Factors Tools in Industry – A Workshop Investigation, Ryerson University, Toronto.http://digitalcommons.ryerson.ca/ie/1/

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Virtual Tools for Assessing Human and Organisational Factors in Production System Design

W.Patrick Neumann (Ryerson University)
Karolina Kazmierczak (Autoliv Inc.)
Per Medbo (Chalmers Univeristy)

Abstract. This paper describes two approaches for integrating human factors into discrete event simulations of production systems. In the first, biomechanical loading information was integrated with a simulation model in a car dismantling operation. In the second study, the productivity sensitivity of three systems with varying parallelisation was tested with respect to a) allowing operators to take breaks 'as desired', and b) having 'reduced capacity' operators at work. Both methods provided insight into design options that gave superior performance with improved ergonomics. Such 'virtual ergonomics' approaches can help establish boundary crossing discussions to support ergonomics application in early design stages.

Keywords. Simulation, Virtual Ergonomics, Production Planning, Productivity

1. Introduction

Simulation permits the prediction of system performance from systems that do not physically exist and allows for testing of parts or configurations of components of those "virtual" systems that are too expensive or dangerous to test in real life (Nemeth, 2004). Discrete event simulation (DES) in particular is rapidly being adopted by industry to help assess the performance impacts of design options. While hundreds of DES-related research papers have been published (Smith, 2003), these typically do not consider the system operators explicitly. Baines et al. (Baines et al., 2004), who see HF as a 'missing link' in DES, have pointed out that *"DES tools represent machines in extensive detail, while only representing workers as simple resources"* with a consequence that models often over-estimate actual system performance. DES is particularly interesting from an ergonomics perspective as it deals with the time-related aspects of work which pose a key element in determining operators' risk (Wells et al., 2007).

This paper reports on two discrete event simulation approaches that explicitly include human factors. The first study, from a car dismantling operation, demonstrates how DES can be combined with human simulation to examine how changes in the work organisation (such as applying team-work) might affect both system performance and operators' biomechanical load. Accumulated biomechanical loads are associated with musculoskeletal disorders (Norman et al., 1998). The second study, based on an engine assembly operation, examines how two different human factors– the ability of operators to take their break allotment as desired and the presence of operators with reduced working capacity - interact with three different system designs with varying degrees of parallelised work flow. The aim of this paper is to provide a methodological overview of these approaches which could easily be adapted to different circumstances. The secondary aim is to report on the lessons learned from the specific analyses. The methods and results from these two examples will be presented sequentially.

2. Methods

All discrete event simulations were conducted according to generally accepted procedures in which a number of factors, such as system configuration, cycle times, time variability, or organisational structures, were systematically tested at two levels, and full factor analysis was used to identify those factors with highest effects on output (Law and Kelton, 1991; Banks, 2001). This paper will focus on the 'Human Factors' aspects of the modelling procedure. All model input data was based on records and measurements from the company's existing or planned production system.

2.1 Methods 1: Integrating Biomechanics into DES

This example is based on a serial-flow car dismantling operation with 5 stations and 2 operators at each station, one on either side of the car (Kazmierczak et al., 2007). The discrete event simulation will report when any given operator is either working (based on the programmed cycle time ranges) or waiting. Waiting may be caused by the system dynamics programmed into the DES model and can include transport times as the vehicles are moved down the line, or by blocking and starving effects as operators wait for their colleagues upstream or downstream along the line.

Biomechanical loading information was obtained for each task the operator performs within the work cycle. In this particular example the WATBAK biomechanical model was used (Neumann et al., 1999 /www.uwaterloo.ca), although other tools for quantifying the mechanical task loading might also be applied. This analysis of tasks was based on a 'representative' operator and a 'typical' cycle. The individual task loads were then combined to calculate a total load for a single work cycle and the waiting time was represented with the loading calculated from an upright standing posture (Figure 1).

During the simulation study a number of different system configurations and assumptions were tested including changes in cycle time, to simulate experienced or novice employees, the use of teamwork in which operators would move between stations to assist their neighbours, and the variability in cycle times to account for the presence of different cars that were easier or harder to disassemble. For each simulation the DES model would provide working time and waiting time to which the biomechanical profile was applied linearly allowing the calculation of total load per shift, along with the usual productivity indicators, for each system configuration that was modelled. In total 4 different system elements were examined with each factor tested at ‘high’ and ‘lo’ levels resulting in a total of 16 simulation trials.

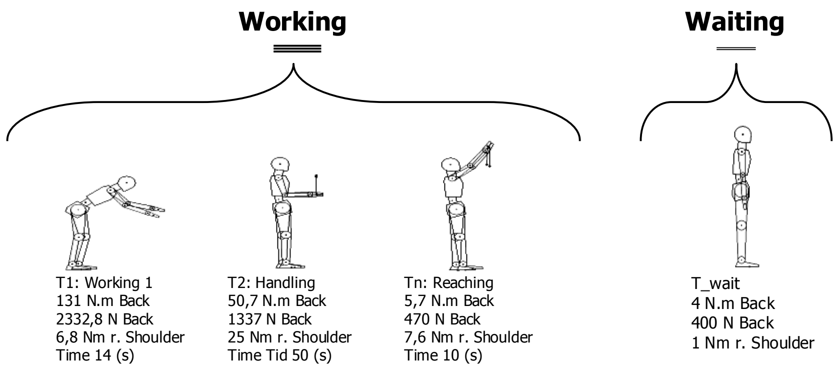

Figure 1: Biomechanical analysis for each task with distinct loading characteristics (T1… Tn) as well as waiting (T_wait) to create a profile of loading and cumulative load for the whole cycle.

2.2 Methods 2: Incorporating Macro Factors into Discrete event Simulations

This DES study was conducted with an engine manufacturer to demonstrate how issues such as ‘job control’, a known psychosocial risk factor for ill health (Karasek and Theorell, 1990), might be incorporated into a simulation . The company had recently moved from parallelised long cycle production to serial flow short cycle production which had resulted in significantly decreased job control and an implied increase in risk (Neumann et al., 2006). The loss of freedom of breaks was reported by employees as one of the drawbacks of the new serial line system implemented at the company. Autonomy in break taking was one human factor, operationalised for testing, by allowing the simulated operators to take their allotted breaks, apart from lunch, ‘as desired’ (modelled as a random distribution) instead of ‘as scheduled’. Additionally, the effects, of the presence of an operator with 50% reduced capacity, were tested to simulate the presence of an injured, novice, or elderly operator. The ability to include older workers and to return injured workers quickly to work were explicit concerns for the management of this company. We refer to these aspects as ‘macro’ human factors as they refer to organisational forms more than the ‘micro’ factors of spinal loading simulated in the first example.

These human factors were tested in conjunction with three different system flow options as the product moved through four production ‘zones’ with 6 stations in each zone. The flows tested included: A ‘chase the rabbit’ scenario where operators followed the product through their production zone; a ‘dual-cell’ scenario where each operator completed half the assembly for their zone; and a full ‘cell’ configuration where operators completed the entire assembly for that zone in parallel with their colleagues before sending their product on (Figure 2). Each of these forms represents an increase in parallelisation of flow. A conventional line system was not tested as it is not capable of handling the organisational forms tested without using additional personnel. Other factors tested included the presence absence of buffers, the amount and distribution shape of cycle time variation, and the presence of product variants with different assembly times. In total 192 conditions were simulated with 5 repetitions each. Results in this case were average hourly productivity for each system configuration.

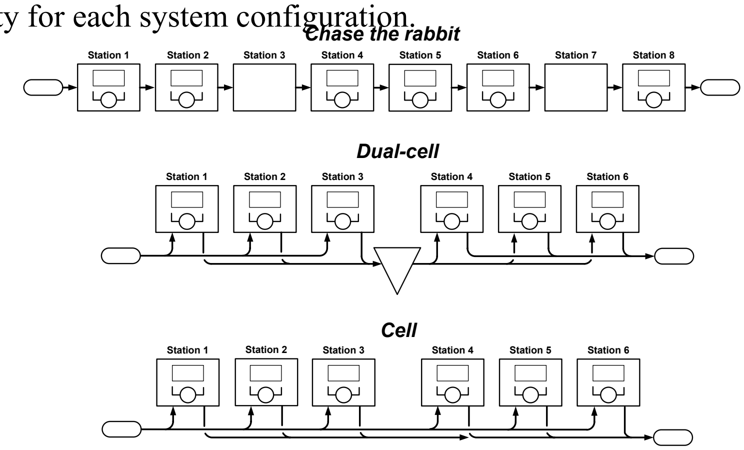

Figure 2: Three system flow options tested in the engine assembly DES study.

3. Results

3.1 Results 1: Biomechanics and Productivity

The car disassembly case resulted in outputs of both productivity (cars per hour) and biomechanical load (N.m.s per shift) for each case which are presented as Z scores so that these indicators could be plotted on the same graph as presented in Figure 3. All system configurations had cumulative lumber moments higher than the average for those reporting low back pain in the automotive sector (Norman et al., 1998).

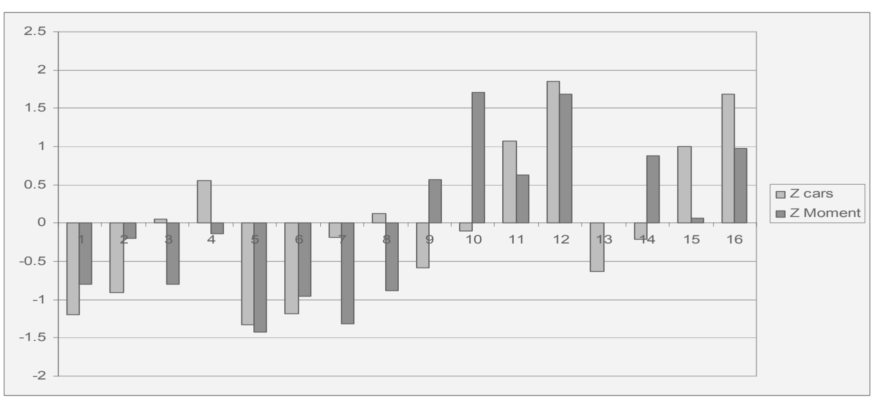

Figure 3: The Z-scores for productivity (Z cars) and for accumulated load (Z Moment) plotted for each simulated case.

3.2 Results 2:The effects of macro HF on system performance

The performance effects of using planned or autonomous breaks, and of having an operator with reduced capacity, on each system is illustrated in figures 4 and 5 respectively.

4. Discussion

The two cases presented here illustrate how both micro (biomechanical load) and macro (break taking and return to work or employment policies) human factor issues can be embedded into discrete event simulation. This suggests great potential for incorporating HF into early stages of production system design where the impact of decisions is greatest and the cost of change is lowest. It also creates potential to frame the examination of HF in productivity terms placing these factors in the same context of other production system design decisions creating a 'common ground' on which engineers and ergonomists might overcome the communication gap observed in efforts to integrate ergonomics into production system design (Kilker, 1999).

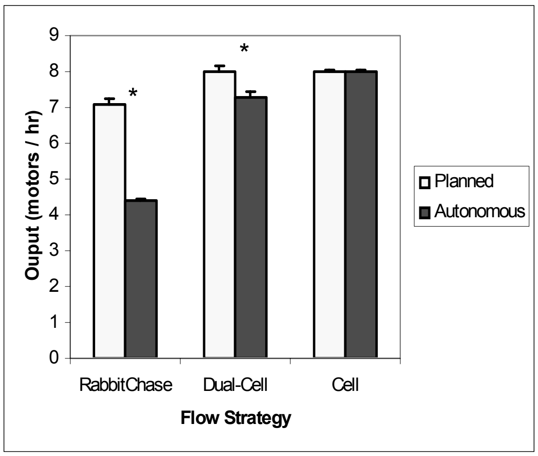

Figure 4: System performance for each flow strategy with planned and autonomous breaks.

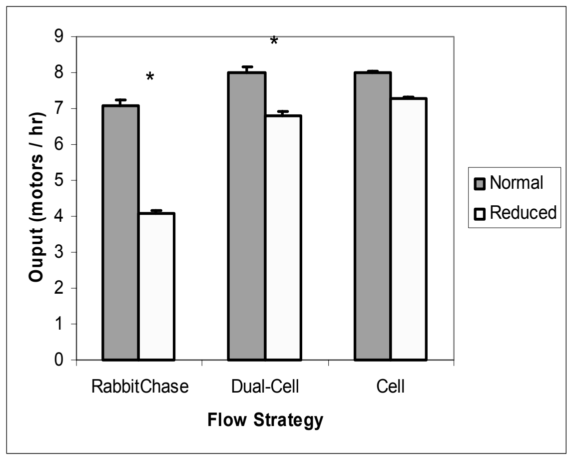

Figure 5: Impact on system performance for each flow strategy of the presence of a 50% reduced capacity operator.

The car disassembly simulation study 1 revealed a number of cases in which high productivity could be achieved with average loading (e.g. case 15), or in which substantially lower loading could be achieved with average productivity (e.g. Case 3). While a single simulation study is rarely conclusive these insights could be used to further refine the planned production system so as to secure satisfactory productivity with low injury risk from accumulated biomechanical loading. The advantages of this approach include relative simplicity (a linear averaging); the ability to incorporate the time gains from improved ergonomics; an approach that is software platform independent; and a biomechanical indicator that is risk-valid. Disadvantages, or opportunities for further development, include the time required to conduct a complete biomechanical task analysis; the difficulty of predicting biomechanical loading in early system design stages; and the exclusion of time and loading variability within tasks. Additionally, this modelling approach risks placing ergonomics concern in direct opposition to productivity concerns as loading and productivity are both linearly related to time.

The engine assembly simulation study 2 illustrated how maco-issues such as autonomous break taking to support a sense of control, or policies supporting the presence of employees with reduced capacity, can be studied in terms of their interaction with flow and work organisation strategies. Unsurprisingly, these policies had least impact on the more parallelised production systems which outperformed serial flows in all situations. Such systems are more robust than serial flows and have been associated with both improved performance and improved psychosocial conditions for operators (Engström et al., 1996; Neumann et al., 2006). Serial flows suffer from more blocking and starving disturbances as well as balance losses and losses created by poor working conditions that lead to demotivated and sick employees (Engström, 1996 #361). It is possible to consider other policies than those modelled here. For example, break taking could be considered as a clustered behaviour as several operators may prefer to take a break at the same time. Similarly if operators are engaged in continuous improvement work, the time required for this might be included in a system model to determine if scheduling policies are needed.

The techniques demonstrated here have good potential to integrate HF into the early stages of production system design. Creating a virtual system that includes a broad range of factors also creates an opportunity for those responsible for different aspects of the system to understand how the strategic choices they make can interact to affect both the resulting system's performance and the system operator's well-being. This boundary crossing potential of virtual analysis tools also creates demands – a variety of skills and knowledge are needed to build these models and no one person in an organisational will generally have this ability. There is a need therefore for a management impulse to ensure that a team with the appropriate skills and mandate is formed to ensure that the necessary system characteristics are included in the model.

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Patrick Neumann
Human Factors Engineering Lab,
Mechanical and Industrial Engineering, Ryerson University, Canada
Per Medbo
Chalmers University, Sweden
Karolina Kazmierczak
Autoliv Inc., Germany

CHALMERS

RYERSON UNIVERSITY

Virtual Ergonomics

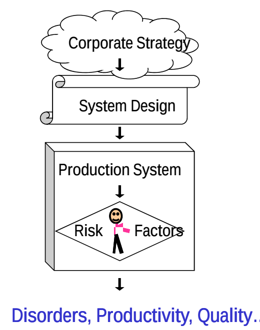
- Applying HF in early design stage before workplace exists physically
  - Checklists or NIOSH eq.
  - Digital Human Models (DHM)
  - Discrete Event Simulation
- Dual Goals: Performance & Well-being

AIM

Demonstrate 2 approaches to 'Virtual Ergonomics':

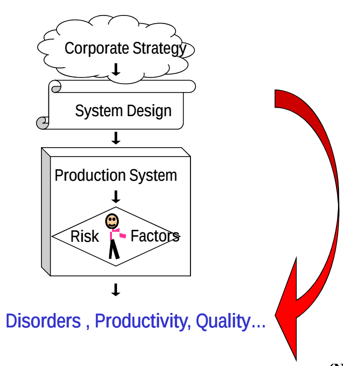
1. Combining Digital Human Models with 'flow' (discrete event) simulation
   – Biomechanics & time
2. Operationalising HF policies in 'flow' simulation for
   – Increased job 'autonomy'
   – Accommodating reduced capacity

Simplified Development Model



(Neumann et al. 2002 IJPR)

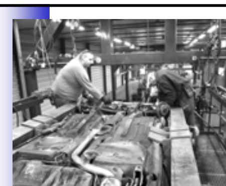
Simplified Development Model



Simulation Predicts Performance

(but GIGO!)

(Neumann et al. 2002 IJPR

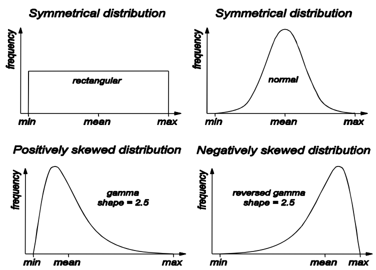


Simulation

- Flow Simulation (descrete event sijm.)
- Human (Biomechancial) Simulation

(Kazmierczak et al. 2007: HFEM)

Time Variability – key factors



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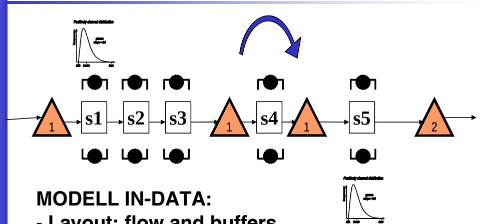
Flow Simulation



MODELL IN-DATA:
- Layout: flow and buffers
- Cycle times & variations
- Transport times
- Cooperation
- Downtime etc.

(Kazmierczak et al. 2007: HFEM)

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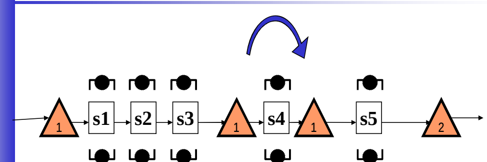
Flow Simulation



Traditional Objective:
-to understand how different system configurations affect system performance

- Generally treats humans as machines

(Kazmierczak et al. 2007: HFEM)

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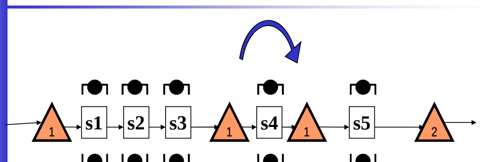
Flow Simulation



New Objective:
- to understand how different system configurations influence *both operator loading and system performance*

(Kazmierczak et al. 2007: HFEM)

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Simulation Study Design

Factor	low	high
A. Experienced operators	4 at 60% + 6 at 100%	10 at 100%
B. Team	no	yes
C. Cycle times:		
Cycle time st 1-3	17 min	10 min
Cycle time st 4	13 min	10 min
Cycle time st 5	10,5 min	10 min
D. CV of cycle times	0,4	0,2
E. Distribution shape	normal	gamma

'LOW" – as observed and measured
'HIGH' – system as designer intended

(Kazmierczak et al. 2007: HFEM)

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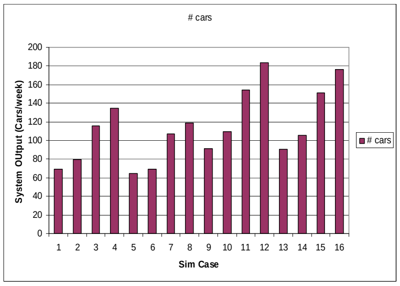
Model Output - # cars / week



(Kazmierczak et al. 2007: HFEM)

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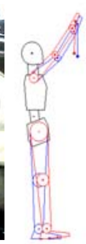
Drivers of Productivity

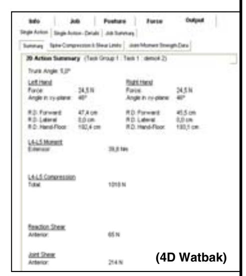
factor or interaction	description	effect (number of cars per week)
C	cycle times	57.6
A	operators' experience	38
D	CV of cycle times	16.9
AC	operators' experience - cycle times interaction	9.2
B	teamwork	-6.9
AD	operators' experience - CV of cycle times interaction	5.1
CD	cycle times - CV of cycle times interaction	4.5
AB	operators' experience - teamwork interaction	3
BD	teamwork - CV of cycle times interaction	-2.4
BC	teamwork - cycle times interaction	-1.7
BE	teamwork - distribution shape interaction	1,15
AE	operators' experience - distribution shape interaction	-1.14
DE	CV of cycle times - distribution shape interaction	0.8
E	distribution shape	-0.25
CE	cycle times - distribution shape interaction	0.1

(Kazmierczak et al. 2007: HFEM)

So, Where's the ergonomics?

Digital Human Model (Biomechanics)

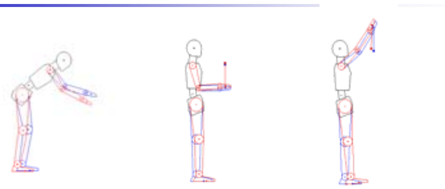




(4D Watbak)

Output: Forces on spine, shoulder etc.
- Peak and accumulated loading

DHM: Biomechanical model



T1: Working 1	T2: Handling	Tn: Reaching
131 N.m Back	50,7 N.m Back	5,7 N.m Back
2332,8 N Back	1337 N Back	470 N Back
6,8 Nm r. Shoulder	25 Nm r. Shoulder	7,6 Nm r. Shoulder
Time 14 (s)	Time Tid 50 (s)	Time 10 (s)

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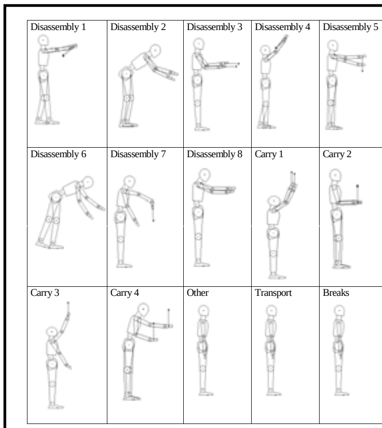

1) **Biomechanical analysis for each action with a different type or level of loading**
2) **Time for each action**

(C.f. Norman et al 1998)

SIMULATION outputs

- Discrete Event Simulation
  - # cars / week
  - Utilisation rate (& idle time) / operator or station
  - Throughput times
  - Blocking, starving, waiting times
- Digital Human Model
  - Postures
  - Spinal (or other) Loading
  - Other? 'load' points etc.

How can we combine these?

Simulation

Typical FLOW SIM MODEL OUTPUT:

'utilised' X% time
'Idle' Y% time

Physical LOADING?

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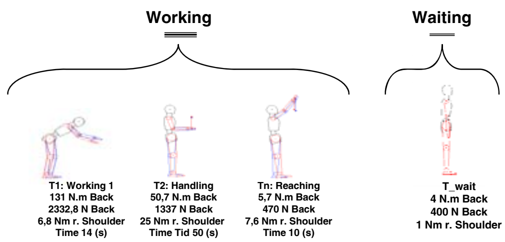
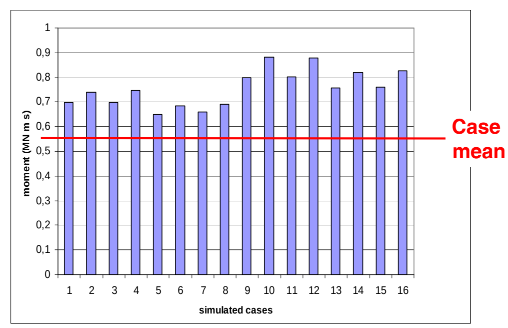
Combining Flow & Human Sim

MODEL: 'utilised' **X% time**
'Idle' **Y% time**



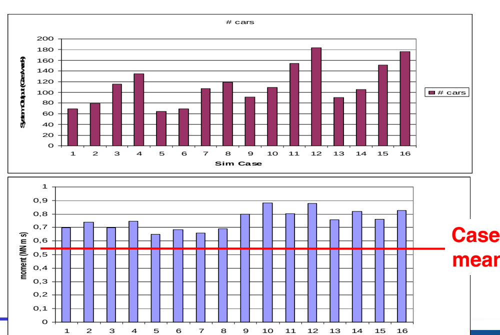
Cumulative LOAD = Work LOAD * X% + Waiting LOAD * Y%

Cumulative Moment for Each Simulated Case…

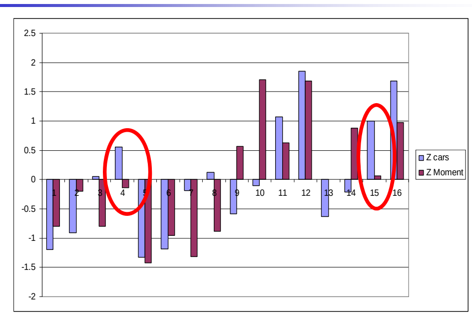


(Kazmierczak et al. 2007: HFEM)

Cumulative Moment for Each Simulated Case…



Hi Productivity & Lo LOAD?



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EXAMPLE RESULTS:
Factors influencing utilisation (loading)

factor or interaction	description	effect (utilization rates)
D	CV of cycle times	9.4
A	operators' experience	7.8
B	teamwork	-2.5
AB	operators' experience - teamwork interaction	2.1
AD	operators' experience - CV of cycle times interaction	2.0
BD	teamwork - CV of cycle times interaction	-1.6
DE	CV of cycle times - distribution shape interaction	1.0
E	distribution shape	-0.8
AE	operators' experience - distribution shape interaction	-0.6
BE	teamwork - distribution shape interaction	0.5
CE	cycle times - distribution shape interaction	0.2
BC	teamwork - cycle times interaction	0.2
CD	cycle times - CV of cycle times interaction	0.1
C	cycle times	-0.06
AC	operators' experience - cycle times interaction	-0.04

(Kazmierczak et al. 2007: HFEM)

Discussion- Strengths

- Simple (linear combining)
- Time based
- Support focus of work-rest scheduling
- Software independent
- Risk-Validated indicators

Discussion - Weaknesses

- Variability inside each task not included
- Time to create assessment of all tasks
- Knowledge needs
- Ergo linearly related to utilisation time – can pit ergo against productivity

EXAMPLE 2

Alternatives to Conventional Line Work

Volvo Powertrain

OLD	NEW
'CELL' Station	'LINE' System

-> Reduced Job Control

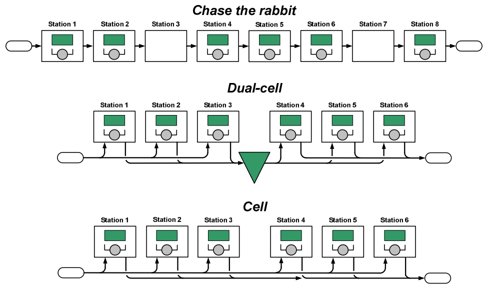
Neumann et al. (2006) IJOPM

Worker perception: reduced Autonomy

"In the old [parallel flow cell assembly] *system, I could work at my own pace. If I was feeling good I could work hard in the morning and then I would have some time. If I had a project, I could do some work on that. Now I just work the whole time. It's boring."*

(Case notes, Sept. 2003)

Three alternative organisations for each production zone…



(No point simulating conventional line flow)

'ERGONOMIC' Factors

Operator Autonomy

- free (random) or strictly scheduled breaks
- Q: Impact on Sense of control?

Operator Pace

- all at 100% or one at 50%
- e.g. Injured, learner, older worker etc.

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'SENSITIVITY' Factors

- Cycle time Distribution shape
  - (normal or gamma)
- Cycle time Distribution size
  - (2.7% or 16%)
- Product Variants
  - (none or 30% taking 12% longer)

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RESULTS: Factor Design Test

Factor or interaction	Description	Effect [engine / h]		
		Rabbit Chasing	Dual Cells	Cells
D	Operator Capacity	-2,13	-1,07	-0,69
C	Rest Breaks	-1,75	-0,40	0,02
CD	Factor C and D interaction	0,99	0,13	0,02
G	Number of Product Variants	-0,20	-0,27	-0,27
F	Assembly Time Coefficient of Variation	-0,17	-0,18	-0,05
DF	Factor D and F interaction	0,13	0,06	
B	Buffer Capacity	0,11	0,38	0,08
CF	Factor C and F interaction	0,09	0,06	-0,003
E	Assembly Time Distribution Shape	-0,01	0,001	-0,004
BC	Factor B and C interaction	-0,03	0,12	0,03
BF	Factor B and F interaction	0,06	0,08	0,02
DG	Factor D and G interaction	0,08	0,02	0,01

5 replications per condition

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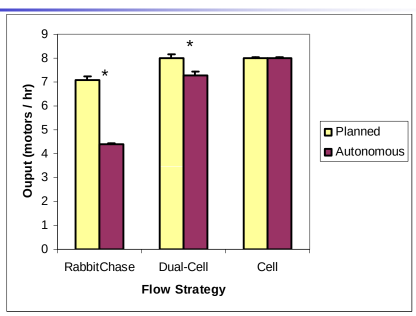
Planned vs. Autonomous Breaks



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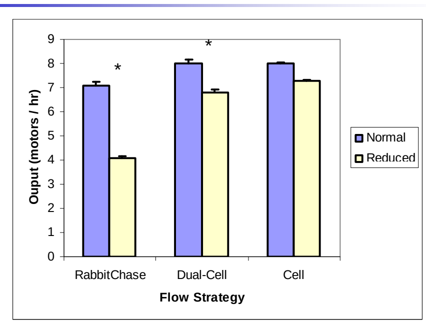
Vulnerability to reduced capacity



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Discussion – Opportunities

- Challenge recovery models could help
- Other load measurement systems possible
- System level focus
- Integrates Ergo & Eng tools
- Needs multiple skills (team)
- Establishes discussion in productivity terms

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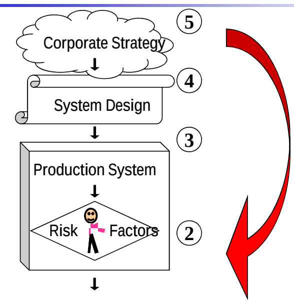
Conclusions?



Disorders, Productivity, Quality...

How to proceed with further research?

- Validation Case studies
- Better HF modelling

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ODAM 2008

(Neumann)