Operator and Machine Models for Dynamic Simulation of Construction Machinery

Reno Filla
Für Onkel Klaus
dem ich für seine Starthilfe beim Einschlagen meiner Ingenieurslaufbahn danke möchte

To my uncle Klaus
whom I want to thank for his little nudge that started my life as an engineer

It's a great thing when you realize that you still have the ability to surprise yourself. Makes you wonder what else you can do, you've forgotten about...

(from the film “American Beauty”)
Abstract

VIRTUAL PROTOTYPING has been generally adopted in product development in order to minimise the traditional reliance on testing of physical prototypes. It thus constitutes a major step towards solving the conflict of actual increasing development cost and time due to increasing customer demands on one side, and the need to decrease development cost and time due to increasing competition on the other. Particularly challenging for the off-road equipment industry is that its products, working machines, are complex in architecture. Tightly coupled, non-linear sub-systems of different technical domains make prediction and optimisation of the complete system’s dynamic behaviour difficult.

Furthermore, in working machines the human operator is essential for the performance of the total system. Properties such as productivity, fuel efficiency, and operability are all not only dependent on inherent machine properties and working place conditions, but also on how the operator uses the machine. This is an aspect that is traditionally neglected in dynamic simulations, because the modelling needs to be extended beyond the technical system.

The research presented in this thesis focuses on wheel loaders, which are representative for working machines. The technical system and the influence of the human operator is analysed, and so-called short loading cycles are described in depth. Two approaches to rule-based simulation models of a wheel loader operator are presented and used in simulations. Both operator models control the machine model by means of engine throttle, lift and tilt lever, steering wheel, and brake only – just as a human operator does. Also, only signals that a human operator can sense are used in the models. It is demonstrated that both operator models are able to adapt to basic variations in workplace setup and machine capability. Thus, a “human element” can be introduced into dynamic simulation of working machines, giving more relevant answers with respect to operator-influenced complete-machine properties such as productivity, fuel efficiency, and operability already in the concept phase of the product development process.
It is traditional for the author to magnanimously accept the blame for whatever deficiencies remain. I don't. Any errors, deficiencies, or problems in this book are somebody else's fault, but I would appreciate knowing about them so as to determine who is to blame.

(Steven Skiena, The Algorithm Design Manual)
THIS WORK, which is a result of many discussions and much practical work, was undertaken at the Department for Research and Development at Volvo Wheel Loaders AB in Eskilstuna and at the Division of Fluid and Mechanical Engineering Systems at Linköpings universitet. I would first like to thank my main advisor Jan-Ove Palmberg and my co-advisers Jonas Larsson and Allan Ericsson for their guidance and support. I would also like to thank my project reference group, consisting of Ulf Peterson, Lars Bråthe, Jan-Ove Palmberg, Jonas Larsson, Allan Ericsson, Conny Carlqvist, Heikki Illerhag, and Bo Andersson for their contribution with ideas, visions, and encouragement.

Especially many thanks I would like to express to Allan Ericsson, Ulf Peterson, and Bo Vigholm for sharing their deep, sometimes philosophical thoughts - not always applicable to conceptual design of wheel loaders, but always relevant. Many more have provided valuable insight, thoughts, ideas, and positive criticism, among them Hans Ericson, Sven-Åke Carlsson, Joakim Unnebäck, Tore Oscarsson, Ulf Nilsson, Lennart Skogh, and Lennart Strandberg. Thank you!

Having come this far in the acknowledgement section, I realise that by starting it I may have opened Pandora’s Box. I have already managed to repeat myself and so many more names come to mind, yet so little space! I sincerely enjoy my time at both Volvo in Eskilstuna and Linköpings universitet, which to a large degree is thanks to all the people I am in contact with, be it in long philosophical discussions or during short coffee breaks. My sincere thanks to you all!

Founding was provided by Volvo Wheel Loaders AB and the Swedish Agency for Innovation Systems, VINNOVA, through the Swedish Program Board for Automotive Research, PFF, which is hereby gratefully acknowledged.

Finally, I would like to express my thanks to my friends for providing an inspiring life outside work (thanks *.* – you know who you are). Oh, and thanks also to the extremely dissatisfying weather over the summer, without which I would have been gliding rather than writing this thesis...

Eskilstuna, August 2005

Reno Filla
THE FOLLOWING THREE papers are appended and will be referred to by their Roman numerals. The papers are printed in their originally published state except for some changes in formatting and the correction of minor errata.

http://www.arxiv.org/abs/cs.CE/0305036

http://www.arxiv.org/abs/cs.CE/0503087

http://www.arxiv.org/abs/cs.CE/0506033

The following paper is not included in the thesis, but constitutes an important part of the background. Because it is written in Swedish, the main ideas have been re-introduced in papers II and III later on.

http://hydra.ikp.liu.se/~renfi/publications.html

(Internet links refer to Technical Reports of the original papers.
Verified on August 15, 2005)
Contents

1 Introduction 13
  1.1 Formulation of the Technical Problem 13
  1.2 Academic Need 14
  1.3 Research Question 14
  1.4 Hypothesis 14
  1.5 Scope and Limitations 14
  1.6 Research Approach 15
  1.7 Research Results 16
  1.8 Project Information 16
  1.9 Thesis Outline 16

2 Background 17
  2.1 Wheel Loaders 17
  2.2 The Harmonic Wheel Loader 19
  2.3 Short Loading Cycle 19
    2.3.1 Force Balance 22
    2.3.2 Motion Balance 23
    2.3.3 Power Balance 25
  2.4 Summary 26

3 State of the Art 27
  3.1 Machine Models 27
  3.2 Environment Models 28
  3.3 Operator Models 29
  3.4 Autonomous Excavation 30

4 Research Approach and Results 35

5 Discussion and Conclusions 39
  5.1 Contributions 40
  5.2 Outlook 40

6 Review of Papers 41

7 References 43
Appended papers

I  Using Dynamic Simulation in the Development of Construction Machinery  47
II Dynamic Simulation of Construction Machinery: Towards an Operator Model  67
III An Event-driven Operator Model for Dynamic Simulation of Construction Machinery  83
EVER SINCE THE INDUSTRIAL REVOLUTION the race has been on to develop and manufacture better products in a faster and cheaper way. Naturally, these days, modern computer technology plays a big part. In the beginning, computers were used to merely substitute the most immediate manual development work, such as drafting, organising product information, and doing calculations. Over time, significant improvements have led to three-dimensional modelling systems, software for product life-cycle management, and powerful simulation packages.

However, for many engineers the product development process still revolves around the traditional properties geometry and strength. The development of other specific product properties is still heavily dependent on testing of physical prototypes. Simulation of large and complex systems has become technically feasible, but there are too few methods available.

This thesis is concerned with how simulation can assist in conceptual design of working machines, in which not only the technical system needs to be considered, but also the working environment and the human operator. The focus here is on understanding and modelling the influence of the operator on the performance of the technical system.

1.1 Formulation of the Technical Problem

Often, product properties arise through complex interaction of sub-systems of various technical domains. Modern simulation techniques can help in examining and purposely designing favourable properties, thus reducing the dependency on testing of physical prototypes. However, in the development of working machines, where the human operator is essential for the performance of the total system, industry only relies on subjective evaluation of physical prototypes by test operators to assess properties such as work productivity, fuel efficiency, and operability. This is not only both time-consuming and costly, but also inherently inaccurate due to the operator’s subjectivity.

To some extent, this inaccuracy is caused by the usual problem of using test results from early prototypes to draw conclusions about the finished product. But, and most importantly, variations in operator performance and environmental conditions lead to low repeatability of the tests, which also makes it difficult to make a reliable assessment of the desired product property’s robustness. The challenge in designing a working ma-
chine such as a wheel loader is to find a balance between such important properties as productivity, fuel efficiency, and operability.

The technical problem is that there are at present no readily available methods for assisting conceptual design of working machines by the means of dynamic simulations, when the human-machine interaction has a major influence on the system properties to be studied.

1.2 Academic Need

Much research has been done on the performance of complex technical systems and on ways to automate work tasks. More research is also been done in the field of human factors.

However, there is little documented research on complex technical systems, where the human operator is not merely a supervisor, but an essential part of the total control system. For such systems, there is a need to derive methods to model the human-machine interaction and to use them to investigate the total systems behaviour and its robustness against parameter variations.

1.3 Research Question

Following the trend described above of increasingly evaluating product properties by the means of computer simulation, the research question for this thesis is therefore how to simulate operator-related dynamic properties of working machines, where the human operator is essential for the performance of the total system.

This includes properties such as productivity, fuel efficiency, and operability, which are all not only dependent on inherent machine properties and working place conditions, but also on how the operator uses the machine.

1.4 Hypothesis

The hypothesis of this work is that by extending the simulation models to not only cover the necessary machine sub-systems, but also include models of the working environment and the human operator, qualitatively better answers regarding the above mentioned complex product properties can be found. There is no need to model the human operator in detail; sufficiently good results can be obtained by implementing principal operator decision models and strategies.

1.5 Scope and Limitations

Naturally, since the research question refers to machinery, where the human operator is an essential part of the total system, the research is limited to such working machines. A wheel loader was chosen as an example, although others can be found not only in the
field of construction machinery, but also among agricultural equipment and in the forestry sector.

The main focus is on the usage of dynamic simulation in conceptual design, an early phase of the product development process. Testing by human operators will always be necessary, but it would constitute a great leap forward if the first iteration loops could be done in a computer simulation, rather than by modifying a physical prototype. Human-in-the-loop simulation has not been considered in this research project. Human-machine interaction and the human decision process have only been researched to such an extent that relatively straightforward operator models could be derived. After all, for the industrial partner in this research project, the expected outcome is a method to arrive at products with specified properties faster.

Co-simulation of models from various domains has been performed, but has not been at the focus of this research. The simulation tools used have been enhanced by subroutines written by the author when necessary, but this has not been a research goal and no research into computational algorithms has been done.

The technical system is considered to work as designed, which excludes the effects of component or system failures on the machine. Later on, methods such as engineering design optimisation and probabilistic design (analytical or experimental) might be applied in order to judge the robustness of a chosen property, but they have not been used in the work covered in this thesis.

For the simulation of the technical system, the intention has mainly been to enhance already existing models, which focus on energy, potential, flow, and their time derivatives/integrals in various domains respectively. Calculation of strength, stresses etc. is not covered. The simulation of the mechanical domain is done using rigid multi-body simulation, hydraulics are simulated one-dimensionally (not using computational fluid dynamics). The drive train components developed by the author are a mixture of one-dimensional models (state equations) and rigid three-dimensional models (like all other mechanical components). The machine’s interaction with its environment is limited to ground contact (via its tyres) and interaction with an already existing dynamic model of a gravel pile (via the loader’s bucket).

1.6 Research Approach

As in all research, the study of relevant literature has had an important part to play. At least equally important has been the study of available knowledge and experience at the industrial partner, which was sometimes found to be undocumented and thus only accessible via personal interviews. The author has participated in several wheel loader development projects, which gave the opportunity to broaden and document knowledge about conceptual design of working machines. Comprehensive test series of physical prototypes and production machines were specified, conducted/supervised, and analysed.

In addition to this practical work, calculations have been performed. A major part of the research work has been the development of two novel operator models, which then have been used in dynamic simulations of complete wheel loaders.
1.7 Research Results

The wheel loader as a complex technical system is explored and possibilities for simulation in the product development process are examined in paper [I] and [IV]. Because understanding the influence of the human operator is a necessity for modelling, new ways to visualise properties such as productivity and operability have been suggested in paper [IV] and are later re-introduced in [II] and [III].

Two different approaches for modelling a human operator have been developed and used for computer simulation of a complete wheel loader operating in a so-called short loading cycle. In paper [II], the focus is on the bucket filling phase, and the human operator is modelled with min/max relationships reminiscent of fuzzy-sets. The operator model presented in paper [III] is realised as a finite state machine (a pure discrete-event approach) and focuses on the remaining elements of a short loading cycle.

Both approaches are shown to have their advantages, but a combination of both seems to be a promising way that still needs to be further explored.

1.8 Project Information

This particular research project constitutes just one instance of a long and successful collaboration between Linköpings universitet and Volvo Construction Equipment. It was partly financed by Volvo Wheel Loaders AB; the other part being financially supported by PFF, the Swedish Program Board for Automotive Research.

1.9 Thesis Outline

The following chapters in this thesis will give the reader an overview of the background, state of the art, research approach, and achieved results. The final chapter contains discussion, conclusions, and some suggestions for future work. For more thorough descriptions of the models developed, the reader is referred to the three appended papers, of which summaries are provided at the end of the thesis.
Background

COMPUTER SIMULATION OF COMPLETE VEHICLES and machines can today be considered to be the state of the art of conceptual design. Especially in the on-road sector, be it on the consumer side (cars) or on the commercial side (trucks and buses), the trend has progressed from simulation of sub-systems to the simulation of complete systems, among other things to evaluate handling, comfort, and durability.

Particularly challenging for the off-road equipment industry is that its products, working machines, are complex in architecture: sub-systems of various domains and their interconnections cause a non-trivial behaviour of the total system.

2.1 Wheel Loaders

In the research for this thesis, a wheel loader was chosen as a perfect example of a working machine. As already pointed out, other examples can be found among agricultural equipment and in the forestry sector.

Wheel loaders are highly versatile machines and are built in vastly varying sizes. The smallest have an operating weight of just 2 tons while the world’s largest wheel loader weighs more than 262 tons. Naturally, not only are there technical differences between these extremes, but also differences in their application. Smaller wheel loaders are often built with a hydrostatic drive train and are used for all kinds of service jobs at smaller construction sites, farms etc. A large number of attachments exist, for example buckets, grapples, forks, material handling arms, cutting aggregates... Machines of this size are purchased for their immense versatility. The opposite is true for larger wheel loaders, which are often bought for one single application: mining. The largest wheel loaders feature a diesel-electric drive train with an electric motor and a planetary gear in each wheel hub.

The research presented in this thesis focuses on medium to large-sized wheel loaders. Figure 1 shows a Volvo L180E with a nominal operating weight of 26 to 29 tons. Such wheel loaders are usually assigned to one specific application, but not limited to mining. Several special attachments exist; there even is a machine variant with a high-lift loading unit for timber loading.
Due to their versatility, wheel loaders need to fulfil a great many requirements, which are often interconnected and sometimes contradictory. Leaving aspects such as total cost of ownership, market availability, reliability etc. aside, the most important machine properties are productivity, fuel efficiency, and operability. Paper [I] gives a more detailed break-down of performance-related aspects and points out that while some of the items are clearly determined by more than just one sub-system (e.g. lift force, which is determined by hydraulics and load unit), others seem to be possible to attribute to one single sub-system (e.g. traction force). One might thus, wrongly, be tempted to leave such aspects out of the optimisation loop when it comes to trading-off product targets against each other when choosing technical solutions. A modern wheel loader, however, consists of tightly coupled, non-linear sub-systems that interact even in seemingly simple cases (Fig. 2).
The power transfer scheme in Fig. 2 visualises how the diesel engine’s power is split up between hydraulic and drive train, which are two parallel sub-systems. Medium to large wheel loaders are usually equipped with a conventional drive train that includes a hydro-dynamic torque converter and an automatic power-shift transmission. Modern wheel loaders feature load-sensing hydraulics with variable displacement pumps. The linkage of the loading unit acts as a non-linear transmission between hydraulic cylinders and attachment.

The next sections will show that the human operator in fact plays an essential role in controlling the total system, a fact that needs to be taken into account when designing a new wheel loader. Electronics can render useful assistance. Essentially all wheel loaders today are equipped with at least one electronic control unit (ECU), often several, each dedicated to one specific component or sub-system, and all ECUs connected to a data bus. “X by wire” is a trend also in the off-road equipment industry, which implies that operators communicate their wishes to the machine via electronics, rather than controlling it directly.

2.2 The Harmonic Wheel Loader

The challenge in designing a wheel loader, from a manufacturer’s point of view, is to find an appropriate, robust, and maintainable balance between productivity (material loaded per time), fuel efficiency (fuel consumed per loaded unit), and operability over the complete area of use.

Productivity and fuel efficiency are well-defined, but a generally agreed definition of operability has still to be found. In [4], a definition is offered, that also works well even for construction machinery: “Operability is the ease with which a system operator can perform the assigned mission with a system when that system is functioning as designed”. The limitation to states where the system is functioning as designed, effectively excludes properties such as robustness and reliability. At Volvo Wheel Loaders, engineers have begun to use the terms Machine harmony and the Harmonic wheel loader as the ultimate goal: A machine that is intuitively controllable and that can be used in a straightforward manner. Everything works smoothly and the work task can be performed without much conscious thought or strategy.

But neither definition gives an explanation as to how to actually quantify operability. Part of this research has therefore been to clarify the concept of Machine harmony and try to develop a method of quantification. This part is still not conclusively finished, but some results are presented in the next section.

2.3 Short Loading Cycle

Because wheel loaders are highly versatile machines, it is difficult to define a standard test cycle that covers every possible aspect of the various tasks and workplaces. However, a so-called short loading cycle (Fig. 3), sometimes also dubbed V-cycle or Y-cycle for its characteristic driving pattern, is highly representative of the majority of applica-
tions. Typical for this cycle is the loading of some kind of granular material (e.g. gravel) on an adjacent load receiver (e.g. a dump truck).

As can be seen in Fig. 3, several phases can be identified in such a loading cycle. In paper [III], ten phases are presented together with a detailed description:

1. **Bucket filling**: The operator fills the loader’s bucket by simultaneously controlling the machine speed and its lift and tilt functions.
2. **Leaving bank**: The loader drives backwards towards the reversing point and steers the machine to achieve the characteristic V-pattern.
3. **Retardation**: Is started some time before phase 4 and can be either prolonged or shortened by controlling the engine throttle and the service brakes.
4. **Reversing**: Begins when the operator judges that the remaining distance to the load receiver will be sufficient for the lift hydraulics to achieve the bucket height necessary for emptying. Operators usually prefer driving a longer distance to waiting in front of the load receiver for sufficient bucket clearance. Reversing is usually accomplished by putting the transmission into forward while the machine is still moving backwards a little.
5. **Towards load receiver**: The operator steers the loader towards the load receiver, thus completing the V-pattern.
6. **Bucket emptying**: The machine is driven forward slowly while at the same time the loading unit is raised and the bucket tilted forward.
7. **Leaving load receiver**: The loader drives backwards towards the reversing point, while the bucket is lowered to a position suitable for driving.
8. **Retardation and reversing**: Not necessarily executed at the same location as in phases 3 and 4, because lowering an empty bucket is faster than raising a full one.
9. **Towards bank**: The machine is driven forward to the location where the next bucket filling is going to take place, while at the same time the bucket is lowered and aligned so that its cutting edge lies parallel to the ground.
10. **Retardation at bank**: Often combined with the next bucket filling by using the machine’s momentum to drive the bucket into the gravel pile, instead of applying traction with the wheels.

Actually, eleven phases could be identified, if phase 8 were divided into **Retardation** and **Reversing**, just like phases 3 and 4. However, the latter have been established as separate phases, because unlike phase 8 they reveal critical aspects of a wheel loader’s design.
The short loading cycle has been established as the main test cycle during development of wheel loaders. Several other cycles exist and are of interest, too, but a short loading cycle reveals any flaw in the following three critical balances:

- **Force balance**: Critical during phase 1, *Bucket filling*
- **Motion balance**: Critical for the cycle time (and thus productivity). In a proper short cycle revealed by the start of phase 4, *Reversing*
- **Power balance**: Especially critical during phases 1 and 4.

The term “balance” here is not to be mistaken for “equilibrium” in a strict physical meaning, but is used to highlight the importance of finding a good solution to the problem of satisfying conflicting demands.

In the following sub-sections, each balance will be described and the reasons for their importance to wheel loader design will be given. It will also be shown that each balance is affected by the way the human operator uses the machine to perform work.
2.3.1 Force Balance

Figure 4 displays the forces and moments of interest during the bucket filling phase of a short loading cycle.

For loading granular material like gravel, the bucket first has to penetrate the pile. This requires traction force, which is achieved by transferring torque from the engine via a torque converter, transmission, axles, and wheels to the ground (Fig. 2). In accordance with Newton’s Third Law of Motion, the Law of Reciprocal Actions, the gravel pile exerts an equal and opposite force upon the loader bucket. A typical sequence for actually filling the bucket is then to break material by tilting backwards a little (i.e. rotation around the lower bucket hinge), lifting a little, and penetrating even further. The lift and tilt functions require engine torque to be transferred via hydraulic pumps (converting torque to hydraulic pressure), cylinders (converting hydraulic pressure to longitudinal force), and loading unit (Fig. 2).

Figure 4 reveals how these two efforts work against each other: in order to achieve a lifting force, the cylinders have to create a counter-clockwise moment around the loading unit’s main bearing in the front frame. At the same time, the reaction force from the traction effort creates a clockwise moment that counteracts the lifting effort.

Because of this, the gravel pile can be seen as a hard coupling between drive train and hydraulics, forcing them to interact with each other, and to experience each other’s effort as an external load. Furthermore, Fig. 2 has already shown that hydraulics and drive train are parallel systems, each competing for the limited engine torque. When these two paths are brought together in the gravel pile, the coupling works like a short circuit, where all loads are transferred back to the origin – the engine. Figure 5 shows this interesting situation, in which engine torque is transferred to the wheels to accomplish traction, but at the same time counteracts that part of the engine torque that has
been transferred through hydraulics to accomplish lifting and tilting – in turn requiring even more torque to be transferred.

Figure 5. Simplified power transfer scheme of a wheel loader loading gravel

This has to be avoided by a design that carefully balances traction and lift/tilt. But these functions can not be optimised without influencing other functions, e.g. machine speed and lifting time. In addition to this, loading unit geometry, and bucket design are of great importance for a smooth bucket filling. Ultimately though, it is the machine operator’s task to achieve a favourable balance by using the available controls. As already pointed out, implementing sophisticated electronic control strategies can be of great help, but each work place is different, and different bucket filling strategies are required for the various materials that exist.

2.3.2 Motion Balance

As mentioned before, an experienced operator chooses the point of reversing so that the bucket will have the necessary height approximately when the loader reaches the load receiver. Figure 6 shows a diagram displaying bucket height over integrated machine speed (i.e. the machine’s travelling distance) in a short loading cycle. The ratio of lift speed to machine speed, which is crucial to how long the loader needs to be driven backwards until reversing, can here be seen as the graph’s slope. The graph is fairly straight from the beginning of phase 2 (where the loader leaves the bank) to the end of phase 5 (where the loader arrives at the load receiver). This indicates that the operator judged well when to reverse. Otherwise, the slope would become steeper at the end of phase 5, indicating that the operator needed to slow down or even stop in order for the bucket to reach sufficient height for emptying.

The distance between the point of reversing and the bank (or load receiver) is an indication of how good a balance has been achieved between the two motions of lifting and driving. Engineers at Volvo CE have begun to call this a Machine harmony diagram, because it visualises aspects that are important for a machine’s operability. Such diagrams are thus useful during development on the system level.
Another interesting aspect is the visualisation of the operator’s technique for bucket filling and bucket emptying (see paper [III] for a more detailed discussion). The chosen bucket filling technique also indirectly influences the position where the loader needs to reverse: Leaving the bank at the beginning of phase 2 with a higher bucket means that it will take less time to raise it from there to a sufficient height for emptying. This means that in theory the point of reversing will be nearer to the bank when leaving with a higher bucket position, because the operator adapts to the machine. It can be shown that this is the case also in practice. Figure 7 shows three selected short loading cycles, originating from a non-stop recording of a longer period, during which the operator changed his bucket filling technique. As can be seen, the bucket height when leaving the bank varies, but the operator succeeded very well in choosing a reversing point in order to reach the load receiver with the bucket at a sufficient height for emptying.
Together with time plots, such Machine harmony diagrams are a useful tool for evaluation of how good a motion balance has been achieved. Additionally, they reveal to a certain degree the operating technique of the human operator.

### 2.3.3 Power Balance

Phase 1, *Bucket filling* and phase 4, *Reversing* are the most challenging phases from an engine’s point of view. Both drive train and hydraulics have high power demands. High traction, lifting, and break-out force are needed during bucket filling, while during reversing, the engine is run at a lower speed and needs to simultaneously cope with increased load from the torque converter and with hydraulic power demand due to continued lifting. The operator’s impression of the wheel loader as a powerful machine depends on either the engine’s ability to satisfy all power demands, the overall machine control system’s ability to govern each sub-system, or a combination of these abilities.

The diagram in Fig. 8 displays data recorded during a short loading cycle. The distribution of engine power to hydraulics and drive train seems on average to be approximately equal, however with large momentary deviations from that rule. Most engine power is required during bucket filling. The oscillations in power and in distribution ratio are a reflection of the operator’s bucket filling technique and the work place conditions.

![Figure 8. Power distribution to hydraulics and drive train in a short loading cycle (total engine power = top of the black area)](image)

Mapping the data displayed above on power requirements to the power available at the current engine speed gives an indication of the wheel loader's performance margins.
2.4 Summary

The human operator plays an active role in simultaneously maintaining all three of the critical balances described above in order to perform the assigned working task. Each of the balances is not only crucial for the wheel loader’s total productivity and fuel efficiency during a loading cycle, but also for its perceived operability.

At the beginning of this chapter, the complexity of working machines was mentioned. In light of all the background information presented, we can conclude that the main challenge with regard to the topic of this thesis is that working machines are complex systems whose main properties productivity, fuel efficiency, and operability are not solely defined by the machine itself, but to a large degree also by how its operator uses it. To a lesser extent this claim can also be made for vehicles (e.g. fuel consumption as a function of acceleration profile or gear shifting strategy), but in the case of working machines the human operator plays a far more significant role. In order to assess a new machine’s productivity, fuel efficiency, operability, and their robustness by means of simulation, one has to model the above described kind of human adaptation to the machine, together with the machine itself and the environment it works in.

The reason for this introduction is to establish that there is a need to expand the view beyond the technical system. In the next chapter, the results of a literature review are given to establish the current state of the art.
State of the Art

Simulation models suitable for complete vehicle/machine simulation have directly or indirectly been a topic of a large number of theses and papers. But these often cover models of the technical system alone. Fewer publications can be found on environment models (typically gravel or soil) and even less on models that additionally cover realistic working cycles by incorporating operator models. In the next sections, relevant results of a literature study will be discussed in the context of this thesis’ research question and hypothesis.

3.1 Machine Models

Naturally, since the goal is simulation of complete machines, most of the machines subsystems and components need to be modelled in a modular way and at various levels of detail. This is usually a collaborative activity. As noted by many researchers, engineers have often already chosen one domain-specific simulation program that they are familiar with. Instead of forcing migration to one monolithic simulation system that can be used in several domains (but offers only limited functionality in the individual domain), a better approach is to couple the specialised, single-domain tools. This has the advantage that both pre- and post-processing are done decentralised, in the engineer’s domain-specific tools. In [1] Larsson examines how interoperability in modelling and simulation can be supported. Part of his work is the development of a co-simulation technique and application to a model of a complete wheel loader.

A conventional hierarchical and modular approach gives the engineer flexibility regarding creation of models with various levels of detail (which parts of paper [I] and [II] elaborate on). Another aspect of modular modelling is that flexibility is gained regarding input data procurement. Planning to reuse an existing model by parameter update implies that exactly the same type of input data is available for the update as it was for the original model. If a diesel engine has been modelled in great detail with hundreds of parameters, then an update is difficult if all the engineer has got is a maximum torque curve. “The more detailed a model is, the more time must be spent on defining the parameters, based on measurements or theoretical engineering reasoning”, notes Makkonen in [5]. Test data might not be compatible due to different measurement set-ups, and theoretical reasoning requires the engineer to reason in a similar (if not identi-
Operator and Machine Models…

cal) way to the creator of the original model. In practice, it might prove more time- and cost-efficient to just develop a new module from scratch, but with an identical interface.

Despite issues with interoperability and input data procurement, modelling the technical system is relatively straightforward (but time-consuming if model validation is taken seriously). Three examples are given in [6]-[8], and many more can be found as success stories on the larger simulation packages’ homepages [2], [3], and others.

3.2 Environment Models

For most work scenarios, a proper environment model might be trivial to achieve. However, this is not the case for bucket loading of gravel or other granular material. In [9] Hemami studies the motion trajectory during bucket loading of an LHD-loader (Load-Haul-Dump). A review of resistive force models for earthmoving processes is made by Blouin et al. in [10]. In [11] Ericsson and Slättengren present a model for predicting digging forces.

Autonomous excavation is in the focus of many works on environment models (including most of the above). Cannon’s work [12] is another example. The technique for online estimation of soil properties described by Tan et. al. in [13] estimates the soil parameters by minimising the error between measured failure forces (obtained via the forces acting on the bucket) and estimated failure forces (the results of an analytical soil model). The failure force is defined as the maximum force that is needed for displacing the soil adjacent to the bucket towards the digging direction. When the compression is too high, the soil breaks away along a line extending from the tip of the bucket to the soil surface.

Another aspect of the environment model is the wheel-ground interaction. Quite a few research papers can be found that explicitly focus on off-road situations. However, neither studying the effects on the ground nor developing a new tyre model is the topic of this thesis. What is needed is a tyre model that is computationally efficient yet sophisticated enough to result in approximately correct traction and wheel loads. Virtually all commercially available tyre models have initially been developed for on-road vehicles with relatively small wheels and medium or high speeds. In order to analyse phenomena at lower speeds these models have later been revised or new ones introduced. However, all of these tyre models need comprehensive input data, regardless of whether they are based on a mechanical model or on scaling of test results. As it seems today, the global manufacturers of large off-road tyres are unable, unwilling, or simply unused to provide these data. Naturally, obtaining test results from large tyres requires the development of large test benches. But there are tyre models that require only a few input data [14] or that can even estimate proper parameters analysing a simplified finite-element model on the basis of certain tire design data [15]. Unfortunately, not even these few basic data can be obtained.
3.3 Operator Models

Traditionally, machine models are controlled by relatively simple algorithms that either prescribe a specific time sequence of input signals or a specific time sequence of output signals.

A first approach can be to simply record a human operator’s control signals, adjust them by filtering, scaling etc, and input them into the model. This method is applicable for situations where a technical system’s reaction to a specific time sequence of input signals is of interest. In complete vehicle simulation, one example could be a brake test or an avoidance manoeuvre to test car stability, like the now-infamous Swedish “moose test” which involves steering at relatively high speed around an obstacle without braking (originally designed to simulate steering around a moose which has strayed onto the road). However, when it comes to simulating working machines in their specific working cycle, this type of forward simulation with fixed input is not sufficient, because it replaces the adaptive closed-loop control of a human operator with open-loop control. The simulation results may be correct, but irrelevant because the output does not match the desired working cycle.

Therefore, inverse (backward) simulation is used predominantly. This method takes a fixed output and calculates backwards in order to obtain the results. One example can be found in engine development, where certain emission test cycles [16] prescribe the vehicle speed as a time series. Another example is in the development of hybrid drive trains. In both cases, fuel consumption is one of the desired results. Such simulations are fast and often used for optimisation, but the problem is that often mere quasi-static calculations are performed, ignoring any dynamic effects. Therefore, current research aims at the inclusion of dynamics into inverse simulation, one example of which is [17] by Fröberg and Nielsen. On the other hand, forward simulation with a fixed output includes dynamics right away, but requires a controlling algorithm, that tracks the prescribed output signal. However, in the case of a working machine any simulation method that relies on fixed time sequences of output signals is flawed, because it ignores the human operator’s ability to adapt (see previous chapter). Forcing a simulated working machine to behave according to a specific output will in many cases result in forced input signals that do not reflect how a human operator would have used the machine. In some cases, it may even result in unphysical results, especially when more than one path for power transfer exists – as is the case for a wheel loader.

Simulation methods with either fixed input or fixed output might work when comparing technical systems of the same architecture and comparable size. However, in some cases even a slight change in the machine setup (e.g. by altering torque converter characteristics) would either require new recorded data (which do not exist yet for virtual prototypes), or would inevitably produce erroneous results, when the working cycle description of the original machine setup was used. In [18] Zhang et al. correctly note: “The experimental evaluation has to consider the human-machine interaction and the task-oriented working pattern specified by a loading cycle”. They acknowledge that in a short loading cycle of a wheel loader “the job is task-oriented, not reference-oriented. The operator is not explicitly following any speed or position reference when driving, steering and lifting. […] The total productivity depends on how well the task is fulfilled,
what the fuel economy is, and how long it takes to finish each cycle. Therefore, the performance and the efficiency of the human-machine interaction need to be maximized”.

The research approach of Zhang et. al. consists of using their own Earthmoving Vehicle Powertrain Simulator (EVPS), which is a combined Hardware-in-the-Loop/Human-in-the-Loop test bed, that represents a certain type of working machine. This means their experiments are human-operated in order to tackle the challenges above described.

Another, earlier, example of using Human-in-the-Loop simulations can be found in [19]. The problem with any form of human operator, be it the operator of a real machine in the field or a virtual machine simulated in a test bed, is that the experiment’s repeatability suffers. Only when computer simulation is used, do extended optimisation runs become feasible. This requires modelling a human operator’s ability to adapt to a new machine and to the working environment, preferably by as simple means as possible.

The simulation of traffic flow, just like road safety is an active research area, where a great many papers, reports, and dissertations can be found. [20] and [21] make valuable contributions by providing insight into human drivers’ function as a vehicle control system. In [22] Vogel combines some existing driver behaviour models and develops her own, control theory-based framework. The existence of a "mental model" of the modelled system enables the driver to anticipate events and act preventively (instead of just mechanically reacting to target deviations). Vogel notes, "It is a very ambitious desire to provide a complete model of driver behaviour, and any such attempt will certainly provoke much criticism. On the other hand, not attempting at least to incorporate the possibility to model all aspects of driver behaviour can be criticized, too”.

As far as working machines are concerned, virtually all attempts published so far have aimed at automation of the excavation process, i.e. at getting rid of the human operator altogether. But in doing so, the researchers needed to analyse working cycles of the machines to automate (essentially wheel loaders and excavators), which makes their work interesting in the context of this thesis.

### 3.4 Autonomous Excavation

Finding suitable strategies and control schemes for robotic excavation has been a relatively active research area for several years. Just like the author of this thesis, researchers in the area of autonomous excavation need to reflect upon working machines, loading cycles, the influence of the environment and the human operator etc. Our research does not involve control strategies or any attempt at automating, but similarities and possibly synergies exist. In the following, three theses are presented in more detail together with reflections on similarities/differences with regard to our own research.

**Singh:**

**Synthesis of Tactical Plans for Robotic Excavation**

In his doctoral thesis [23] from 1995, Singh develops an approach to planning of autonomous excavation. He observes that the task of excavation can be broken down into three large problems. The first is to find an optimal way to divide the entire work-site into smaller locations, from which the excavation work will be performed in sub-
tasks. Secondly, the sub-task at each location needs to be broken down into single digging operations, resulting into a set of optimal trajectories. Thirdly, these trajectories need to be executed as closely as possible. Singh’s thesis focuses on the second of these problems, during which, as he notes, “the planner must reason about the kinematics of the mechanism, the shape of the terrain, the resistive forces experienced during excavation and the torques that can be delivered by the actuators.” Each of these points constitutes a constraint, and the problem of tactical planning can be handled as a constraint optimisation in the space of feasible actions.

Even though Singh uses wheel loaders and excavators in the tasks of loading and trenching as examples throughout his thesis, his general approach is machine- and task-independent. Tasks are described as trajectories of the digging tools, the machine’s actual linkage is considered by means of a reachability constraint. This is one of three geometric constraints, which describes whether the machine can accomplish the trajectory without going outside its workspace. The other two geometric constraints are shaping and volume. Shaping describes the resulting terrain after excavation. For loading, it would demand that no trajectory requires the digging tool to cut below ground level. Finally, the volume constraint ensures that not more material will be excavated than the bucket can hold.

Because real machines have only limited power and strength, another type of constraint need to be considered: force constraints. This requires the prediction of excavating forces, for which Singh develops and compares three learning methods: global regression, neural nets, and memory-based learning. All methods require the collection of force and topological data during prior digging experiments.

Combining all of the above in a constraint optimisation method in order to determine the optimal tactical plan proved difficult. Singh shows that analytical closed-form solutions are not possible, due to the fact that the state space is large and that the differential equations modelling the soil-tool interaction are not given in closed form. Instead, one-step planning is proposed. The problem with this is that the emerging sequence of trajectories will be suboptimal, because of the emphasis on short-term benefits. As Singh notes: “In the general case, it is possible that the robot will choose and execute a one-step plan that will keep it from completing the entire task. That is, it might find itself in a local extrema [sic] in the underlying state space and the only way to progress will be to first undo some work done.” Unfortunately, he does not suggest any answers to this problem and “assumes that a strategic planner that provides sub-goals will ensure that such a case doesn’t occur”.

Singh implements his methodology in a simulation model and in a real digging robot, a hydraulic manipulator that performs digging experiments in a soil box. He observes that “the real world is much less forgiving than simulated scenarios”. The physical implementation features a laser scanner to build elevation maps and a force sensor, the latter deemed by Singh to be “absolutely essential for autonomous excavation”.

When comparing Singh’s work with our research, one can see that there are in principle two completely different motivations: Singh wants to automate the excavation process and thus needs to handle strategic planning, which is normally done by human operators. In contrast to this, the motivation for our thesis is to use simulation to evalu-
ate working machine properties such as productivity, fuel efficiency, and operability – which are all influenced by the way the human operator uses the machine. Strategic planning is of no greater interest in such assessments, because only one loading cycle is considered. Unlike our studies, Singh’s work looks at a collection of optimal loading cycles, but does not consider the execution of found trajectories. Both works thus stand in their own right, with no serious interference. However, similarities exist and Singh’s research may prove to be applicable later on. For now, the main difference remains that our work aims at the simulation of human operators as a way to improve working machines, while Singh’s work aims at automating the excavation process and abolishing human operators altogether.

Marshall:
Towards Autonomous Excavation of Fragmented Rock [...] 

Marshall’s master’s thesis [24] from 2001 focuses on the problem of autonomous excavation using a special type of wheel loaders: load-haul-dump (LHD) underground mining machines. A wide range of full-scale experiments on bucket filling were conducted under excavation conditions comparable to those found in an underground mining situation.

As part of the work, excavation trials were conducted by professional operators in material of varying particle size and composition. In these experiments, some machine parameters such as translation and hydraulic cylinder forces were recorded, while other parameters such as the operator’s command input signals and tractive effort, were not considered. As Marshall argues at the end of his thesis, the operator’s input signal “might possibly have allowed for improved identification of the excavation process based on purely operator (control signal) inputs, avoiding the causality issue, and perhaps permitting simulation or even prediction of the bucket-rock interaction intensity level”. Furthermore, due to significant wheel slippage, the vehicle's translational motion could not be measured correctly, and the tractive effort was not measured at all. Marshall writes that “an assumption was made that any tractive effort supplied by the vehicle was generally constant throughout the loading operation, and that tractive effort control would not have provided any significant contribution to solving the autonomous excavation problem.” The focus was thus given to the problem of determining appropriate bucket motions in order to achieve a full bucket of material. Marshall later acknowledges that the above assumption with regard to tractive effort was flawed.

Based on these measurements, Marshall then models the loader’s linkage motions during excavating, using parallel cascade identification (PCI), a nonlinear system identification technique. Three other methods are also discussed, but PCI was the one adopted. However, dynamic problems especially when identifying dump cylinder motions in free-space led to outcomes that were “not exceptionally good”. Marshall can show that changes in dump cylinder force correspond well to changes in the cylinder velocity, and reasons: “The question therefore remains as to whether the model input velocity changes [...] are due to bucket-rock interaction, or due to signals commanded by the operator. Strictly speaking, the answer is likely that both are responsible [...]. If the operator in fact commanded significant changes in cylinder velocity, then a control
system for autonomous excavation should perhaps not only respond to variations in bucket-rock interaction intensity, but also *induce* such changes, so as to fluidize the rock pile during scooping”.

Finally, Marshall argues for approaching the formulation of a control system design via admittance control, which dictates that the manipulator accepts force and responds with motion. This results in the development of a velocity-based force compensation scheme.

Potentially, Marshall’s work could have provided valuable insight into human-machine interaction during bucket loading of fragmented rock. However, the explicit focus on automating the machine motions while neglecting the human operator’s contribution to the loading process is a significant difference in approach compared with our own research.

**Wu:**
**A Study on Automatic Control of Wheel Loaders in Rock/Soil Loading**

In Wu’s doctoral thesis [25] from 2003, too, the focus is on the development of a controller that can control bucket and machine motion during digging. Using material won via personal interviews with professional operators, literature study, and statistical analysis of full-scale experiments, Wu reflects thoroughly upon the loading cycle and a human operator’s techniques and strategies.

The parts of the loading cycle that Wu focuses on are attacking, crowding, and scooping (Fig. 9). Using the phases identified in section 2.3, this would mean phases 10, *Retardation at bank*, and 1, *Bucket filling*, while the manoeuvring before and after would be phases 9, *Towards bank*, and 2, *Leaving bank*. It is interesting to see that Wu has split the bucket filling into different phases, but an analysis of their respective control strategies shows that essentially the same process is described.

![Figure 9. Operations of a digging task, according to Wu [25]](image-url)
The developed controller creates an ideal trajectory in advance, based on bucket volume, workspace, and rock pile parameters. During digging, this trajectory is roughly followed, but adjustments are made to machine speed and bucket position. Wu recognises that different material properties require variations in the scooping strategy, and identifies three usable strategies, labelled as “easy-scoop”, “normal-scoop”, and “hard-scoop”. “Hard-scoop” implements small oscillations in bucket tilt angle, while in “easy-scoop” the bucket is tilted backwards faster than in “normal-scoop” and without any oscillation. Wu makes similar considerations regarding the crowding phase, and reflects upon repeatability in order to ensure that the same principal bucket filling methods are also applicable to the next loading cycle.

Machine speed control is an aspect for which Wu uses statistical analysis instead of arguing for a specific strategy. He finds an approximate relationship between engine speed and bucket tip height, which is then implemented into the developed digging controller. This controller is adaptive, which ensures continuous improvement of the accuracy with which machine speed and bucket penetration depth are predicted. Wu also investigates the occurrence of wheel slip and develops an algorithm for detecting it through sensor fusion. A strategy for wheel slip reduction is then implemented into the digging controller.

The models that are developed in Wu’s thesis are statistical, non-physical models that are constructed with neural nets. Human decision-making is approximated with the help of fuzzy logic, which also ensures insensitivity to sensor noise. Wu verifies the developed controller in a series of simulation experiments (implementing it into a real machine is left for future work).

Since the focus of Wu’s work is on the development of an adaptive digging controller, it is natural that there are different priorities in comparison to our own research. The most obvious difference is the concept of an ideal bucket trajectory, compared to the event-based operator models in our own work. However, Wu’s thesis offers valuable insights into working techniques and strategies of human operators, which are comparable to the results of our own experiments. Wu does not analyse the technical system to any great extent (except for the loader’s linkage), and thus makes no reasoning regarding power transfer etc., but his principle work on the adaptive digging controller may in future research be applicable to a refined operator model.
Research Approach and Results

APPLICATION-ORIENTED RESEARCH has been performed by the author, aimed to increase the knowledge about wheel loaders as complex technical systems in general, and about interaction with human operators in particular. The study of publicly and internally available literature has been of importance, but equally important have been the personal interviews conducted with fellow engineers and professional wheel loader operators.

The author has participated in several wheel loader development projects, which provided an opportunity to broaden and document knowledge about conceptual design of working machines. Comprehensive test series of physical prototypes and production machines were specified, conducted/supervised, and analysed. In addition to this practical work, calculations and dynamic simulations have been performed. This also gave the opportunity to reflect upon the role of dynamic simulation in the product development process, and in general upon simulation techniques and methods. Most of the simulation models used have been developed collaboratively by the author and fellow engineers.

The publicly available results of this work can be found in four published papers, of which three are appended to this thesis. In the fourth paper, which is available in Swedish only, novel ways to visualise operator-influenced properties such as productivity and operability are explored. The most promising visualisations are then re-introduced in the appended papers.

Two different approaches for modelling a human operator have been developed. They have in common that the operator model is logically separated from the machine model, which is controlled through variables representing the functions engine throttle, brake, steering, lift, and tilt. Operator model and machine model act as black box models towards each other. No internal states are sent, because the intention is to model human-machine interaction, which naturally occurs through a limited number of channels. In the modelling setup for the second operator model, this has been realised by co-simulation: the wheel loader is modelled and simulated in a multi-body simulation program, while the operator is completely modelled and simulated in a software package that supports both continuous and discrete event simulation. The operator model sends
commands through the machine controls, which the loader model receives, uses and answers with e.g. loader position and orientation, and engine speed (Fig. 10).

In the focus of the first operator model has been the bucket filling phase, and the human operator is modelled with min/max relationships reminiscent of fuzzy-sets. The rules upon which this model is based cover control of bucket motion and wheel traction. Figure 11 shows the results of one specific simulation.
This approach proved to be successful in the bucket filling phase of a short loading cycle, but less so in the remaining phases. A second operator model has therefore been developed, which is realised as a finite state machine (a pure discrete-event approach) and focuses on the remaining elements of a short loading cycle. Figure 12 shows the overall view of the operator model, where each phase has been modelled as a state containing several sub-states.

Figure 12. Event-based operator model (top level view)

Figure 13 displays the machine movement in a simulated cycle. Figure 14 represents the results of the same simulated cycle in a machine harmony diagram (see also 2.3.2). Only half a harmony diagram is shown because neither bucket filling nor the phases after bucket emptying are included in the current version of this operator model.

Figure 13. Simulation of a short loading cycle: resulting machine motion
In the simulations conducted, both approaches to an operator model are shown to be able to adapt to variations of system parameters such as torque converter characteristics, lifting speed, or work place setup.
TWO DIFFERENT APPROACHES to a rule-based operator model have been developed. Despite their differences, both are able to adapt to basic variations in workplace setup and machine capability. Thus, a “human element” can be introduced into dynamic simulation of working machines, giving more relevant answers with respect to operator-influenced complete-machine properties such as productivity, fuel efficiency, and possibly even operability. This can be used to significantly support the product development process by substituting many tests of physical prototypes with equivalent tests of virtual prototypes.

In 1.1, the technical problem is formulated as “that there are at present no readily available methods for assisting conceptual design of working machines by the means of dynamic simulations, when the human-machine interaction has a major influence on the system properties to be studied”. With the results of this research, a solution is imminent. However, using dynamic simulation to assess operability of working machines still requires more work.

The academic need, described in 1.2 as “a need to derive methods to model the human-machine interaction and to use them to investigate the total systems behaviour and its robustness against parameter variations” has mostly been satisfied; however not fully, because no investigations of robustness have been conducted yet.

This work’s research question is formulated in section 1.3 as “how to simulate operator-related dynamic properties of working machines, where the human operator is essential for the performance of the total system”. The associated hypothesis is described in 1.4 as “that by extending the simulation models to not only cover the necessary machine sub-systems, but also include models of the working environment and the human operator, qualitatively better answers regarding above mentioned complex product properties can be found. There is no need to model the human operator in detail; sufficiently good results can be obtained by implementing principal operator decision models and strategies”. This has clearly been demonstrated. It can thus be argued that an answer to the research question has been given, although there is still future work that needs to be attended to.
5.1 Contributions

The main contribution of the research presented in this thesis is the demonstration that by implementing principal operator decision models and strategies, computer simulation can be used to evaluate operator-related dynamic properties of working machines. The demonstrator in this thesis is a wheel loader, but other areas of application can be found not only in the field of construction machinery, but also among agricultural equipment and in the forestry sector.

Another contribution of this thesis is that knowledge about wheel loaders as complex technical systems in general, and interaction with human operators in particular is broadened and documented. Also, the machine harmony diagram as a novel visualisation of a wheel loader’s motion balance is presented, which can assist in indirectly evaluating operability.

5.2 Outlook

Quantifying operability is much harder than quantifying productivity and fuel efficiency. However, it should be possible to use the results of existing research into mental workload, possibly connecting an operability measure with the operator’s efforts to control the power distribution between hydraulics and drive train. If such a measure could be found, then simulation would be of great assistance in optimising machine characteristics for example for maximum fuel efficiency or robust operability (the latter both with respect to component tolerances, varying environmental influences, and different operator skills). One approach to quantification might be through the definition of an operator input dose similar to vibration dose value in the assessment of whole-body vibration exposure.

A thorough validation of the operator models developed needs to be performed, possibly in combination with personal interviews in order to sample the test operators’ impressions of operability and compared with any proposed quantification method.

While the operator model presented in paper [II] focuses on the bucket filling phase and uses an approach with relationships analogous to fuzzy-sets, the operator model presented in [III] focuses on the remaining elements of a short loading cycle and uses a pure discrete-event approach. It is advantageous to use this modelling paradigm, but certain elements such as path control are probably best modelled with a simple PI-controller. Therefore, in the next version of this operator model the possibility of combining these approaches needs to be explored. Another possibility is to use inspiration from the adaptive controllers developed in the presented research on autonomous excavation.
Review of Papers

Paper I

Using Dynamic Simulation in the Development of Construction Machinery

The paper essentially describes the technical problem and the academic need. It gives an overview of the research project, and explores the challenges of the wheel loader application. The results of a literature review are listed, and future research possibilities are examined together with possible solutions. Reflections are made upon the role of dynamic simulation in the product development process, and upon simulation techniques and methods in general. A revised product development process with regard to the research topic is proposed.

The main contribution of this paper is to provide a basis for formulation of the research question of this thesis, as well as its hypothesis. All research leading to this paper and the writing of the paper itself is the work of the main author. The paper’s co-author provided valuable feedback.

Paper II

Dynamic Simulation of Construction Machinery: Towards an Operator Model

A first version of a rule-based operator model is developed. With the focus on the bucket filling, one specific technique of human operators is described in detail. The operator model consists of min/max relationships reminiscent of fuzzy-sets and is shown to work well. Its ability to reproduce human adaptation to basic variations in machine capability is demonstrated. Besides this, reflections are made upon modular simulation and level of detail, power transfer in a wheel loader is examined, and the question of quantification of operability is raised.

The main contribution of this paper is in the description and successful modelling of one bucket filling technique of human operators. All research leading to this paper and
the writing of the paper itself is the work of the main author. The framework and the machine model used in the simulations are a collaborative work by the main author and two fellow engineers, one of them being the paper’s first co-author, Allan Ericsson, who also did most of the actual development of the operator model. Both co-authors of this paper provided valuable feedback during research and writing.

Paper III

An Event-driven Operator Model for Dynamic Simulation of Construction Machinery

The paper gives a thorough description of a wheel loader’s short loading cycle. A second operator model is developed, which is realised as a finite state machine (a pure discrete-event approach) and focuses on the remaining elements of a short loading cycle. Neither bucket filling nor the phases after bucket emptying are included. It is demonstrated that this operator model is able to adapt to basic variations in workplace setup and machine capability. The machine harmony diagram as a way to indirectly visualise important aspects of operability is re-introduced.
References


http://www.lmsintl.com/?sitenavid=00F6F4FF-A434-4634-9FA4-F7517E60B72B


http://www.lib.kth.se/Fulltext/makkonen990525.pdf


http://dx.doi.org/10.1109/28.315248

http://dx.doi.org/10.1061/(ASCE)0893-1321(2001)14:3(102)


http://www.ri.cmu.edu/pubs/pub_2103.html

http://dx.doi.org/10.1109/TMECH.2005.844706

http://www.delft-tyre.com

http://www.ftire.com

http://www.dieselnet.com/standards/cycles/index.html


http://mr-roboto.me.uiuc.edu/evps/papers/imece03_cycle/ imece2003-41282.pdf
http://members.asme.org/catalog/ItemView.cfm?ItemNumber=I416CD0404315

http://www.control.lth.se/publications/lic/documents/ben01lic.pdf

http://dx.doi.org/10.1076/vesd.40.1.101.15875


http://www.frc.ri.cmu.edu/~ssingh/pubs_thesis.html


http://wwlib.umi.com/dissertations/fullcit/3090033

(Internet links verified on August 15, 2005)