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# Effective Development of Dynamic Systems - a Structured Approach

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# Effective Development of Dynamic Systems

## A Structured Approach

by

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Luleå 1999

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## Preface

The research presented in this thesis has been carried out at the Division of Computer Aided Design at Luleå University of Technology in Sweden. The research project was initiated by my main supervisor Associate Professor Annika Stensson and my co-supervisor Professor Lennart Karlsson.

I wish to express my gratitude to my supervisors for giving me inspiration, support and stimulating discussions throughout this work. I especially want to thank my close co-authors Lars Drugge and Henrik Johansson for interesting discussions as well as valuable support. Many thanks to my colleagues and friends at the Division of Computer Aided Design for creating a nice working atmosphere.

The gratefully acknowledged financial support has been provided by the Swedish Foundation for Strategic Research, and the Swedish National Rail Administration. The research has been conducted within the ENDREA[1] research program and ENDREA has contributed with a valuable research network as well as interesting courses.

Finally, I would like to thank my family, and especially Madelene for putting up with me and encouraging me during the times when my work has taken all my hours.

Luleå September 1999

Tobias Larsson

[1] ENDREA – The Swedish Engineering Design Research and Education Agenda

## Abstract

This licentiate thesis deals with effective simulation of multibody dynamic systems in the product development process. Previous work to make simulation more effective has concentrated on developing faster calculation methods. Instead, this approach is to make the process of multibody dynamics simulation more effective by structuring of products, simulation models and their usage.

Efforts have been made to clarify how computer tools are used in product development in industry today. Insight into the two domains of product development and multibody dynamics is given. These domains have traditionally been separated but the introduction of concurrent engineering and faster computers puts new demands on the integration of computer support and analysis in the development process.

A proposal for performing the multibody dynamics methodology in a modular way in the product development process is given based on the performed work.

## Keywords

Dynamic analysis, multibody dynamics, product development process, modular design.

## Thesis

This thesis comprises an introductory part and the following papers:

**Paper A**

JOHANSSON, H. & LARSSON, T. (1998) *Information Flow and Simulation Support in the Product Development Process - A Case study*, Proceedings of Produktmodeller-98, pp. 271-280, Linköping, Sweden.

**Paper B**

LARSSON, T. & JOHANSSON, H. *Product Modularisation with Respect to Dynamic Analysis.* To be submitted for publication.

**Paper C**

LARSSON, T. & DRUGGE, L. (1998) *Dynamic Behaviour of Pantographs due to Different Wear Situations*, Computers in Railways VI, Ed. Mellitt et al. WIT press, pp. 869-880.

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# Appended Papers

**Paper A**

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# 1 Introduction

The competitive situation arising with the globalisation and intensification of the manufacturing industries makes it important for industry to keep lead-time short. Besides time-to-market demands industry also has to deal with limited budgets although the product complexity is growing. Customer requirements and expectations must be met while maintaining quality. This competitive situation motivates companies to ensure their capability to produce successful products in terms of market shares and product profit.

In order to achieve the successful development of products, companies must strive for an understanding of the own company processes, methods and tools used when developing the products [1,2,3]. When this understanding is achieved it is possible to restructure and enhance the different company tasks and perform world class product development [4].

The last decades rapid development and implementation of computer based tools have had great impact on the product development processes. Especially, the area of Computer Aided Design, CAD [5], has changed the best practice of how to develop products. Here, development of computers, productivity and design tools as well as special tools like analysis and simulation software has created a number of new engineering disciplines.

Consequently, these specialised disciplines have to be integrated in a simultaneous, or concurrent, engineering process [6,7] where all the relevant activities, such as design, analysis, testing and manufacturing are involved early on in the development process. This approach creates the possibility to make correct decisions in good time and hereby reduce lead-time.

Among the tools for design of mechanical systems, computer aided simulation techniques for mechanical dynamic systems, multibody dynamics [8,9], have a large potential in product development. But they are only partly used today due to modelling and simulation complexity. In order to make it possible for a design engineer, and not only for a specialist in dynamics, to use simulation methods for effective development of dynamic systems the complexity of the procedure for using them must be reduced.

This licentiate thesis deals with effective simulation of multibody dynamic systems in the product development process. The aim of the work is twofold; to perform advanced dynamic simulations in order to predict the dynamic behaviour of the studied systems and at the same time to clarify the methodology and task process of advanced dynamic mechanical system analysis in the product development process. Traditionally, the domains of product development and simulation have been separated but the introduction of concurrent engineering and faster computers puts new demands on the integration of computer support and analysis in the development process.

A proposal for performing the multibody dynamics methodology in a modular way in the product development process is given based on the performed work.

## 1.1 Product development

Product development has been defined by Ulrich & Eppinger [10] as

*"the set of activities beginning with the perception of a market opportunity and ending in the production, sale and delivery of a product"*

In a company, the product is typically described as a process, the product development process. This product development process is often specific for the company since the manufactured product highly describes the process. There are a variety of methodologies for understanding and enhancing the product development process. These theories mainly consist of literature and studies establishing a view of how to perform good product development and how to structure the company processes [7,11,12].

An effective product development process requires communication and co-ordination of market efforts, design and production [7,13,14]. The development tasks should also be carried out in parallel rather than sequential. Overlapping activities are one of the key factors to the increasing information flow between different processes in the development [12,15]. As a result, the different methods for performing the tasks have to be modified to correspond to the higher demands of integration. Overlapping and cross-functional co-operation are essential in the approaches of Integrated Product development and Concurrent Engineering, or Simultaneous Engineering, [13,16,17,18,19] which have had a lot of attention in the last decade. These approaches focus on:

- Improvement of quality.
- Reduction of life cycle costs.
- Reduction of development lead times.

Simultaneous engineering has been defined by Winner et al. [19] as

*"a systematic approach to the integrated, concurrent design of products and their related processes, including manufacture and support. This approach is intended to cause the developers, from the outset, to consider all elements of the product life cycle from conception through disposal, including quality, cost, schedule, and user requirements"*

Cleetus [20] has proposed a new definition:

*"CE is a systematic approach to integrated product development, that emphasizes response to customer expectations and embodies team values of cooperation, trust, and sharing in such manner that decision making proceeds with large intervals of parallel working by all life cycle perspectives, synchronized by comparatively brief exchanges to produce consensus"*

Both of the above definitions address the importance of a systematic approach. The area of product structuring when developing products is also of high interest today since industry has to arrive at a product design that has been systematically optimised in order to meet customers needs and still satisfies a large market variety. These in terms of products for mass customisation, but also to products with lower volumes. One proposed method for dealing with the above questions is to use a modular approach in the development of the products. This since the modular approach with building blocks, modules, claims to give reduced lead-time, improved quality, high flexibility as well as retaining low costs [21,22,23,24,25]. By using work made in this area and apply it to the area of simulation, modelling benefits can be achieved. Comprehensive work in this area is performed by [26,27,28,29]. Structuring products into modules with the help of the Modular Function Deployment, MFD, method is described by [30].

### 1.2 Computer simulations

Computational methods, in this work defined as methods to find approximate solutions to mathematically described models of real systems, have had large impact on product development the last decade. Model definition might be according to Neelamkavil [31]:

> *"A model is a simplified representation of a system (or process or theory) intended to enhance our ability to understand, predict, and possibly control the behaviour of the system"*

Since the techniques for modelling and simulation are becoming mature, the industry is getting more eager to use them. A beneficiary factor here is the implementation of 3D CAD models into the design stages of product development. Presently, CAD is not particularly effective in the initial synthesis of design or in the redesign portion of the design loop [8]; however, it is very useful in providing more efficient ways to help the designer revise the design. A simple sequence of new design commands can cause a wide range of changes throughout the design.

The rapid development and implementation of new tools allows CAD to be used in a greater part of the development chain. CAD systems are usually not well integrated with current simulation techniques although the simulation techniques are well developed. However, integrated analysis is possible where CAD models can be used for creating Finite Element Models for structural analysis, dynamic models for simulation of motion or for performing Computational Fluid Dynamics simulation.

The computer tools typically consists of aids for design, analysis, drafting, process planning among others and are often mentioned as computer aided engineering, CAE, tools. I-DEAS, ProEngineer, SolidWorks, ANSYS and ABAQUS [32,33,34,35,36] are some of them. The CAE tools are typically implemented with a stronger emphasis to the detail design phase in the product development process where iterative computer simulations are extensively used to find design optimum and where the major design parameters are defined.

### 1.2.1 Multibody dynamics

Dynamics is the area of mechanics that deals with the motion of bodies under the action of forces. Dynamics has two distinct parts – *kinematics*, the study of motion without reference to the forces that cause motion, and *kinetics*, which relates the action of forces on bodies to the resulting motions.

Historically, the rational understanding of dynamics is credited Galileo (1564-1642), although it was Newton, guided by Galilee's work, who was able to make accurate formulation of the laws of motion and hereby place dynamics on a sound basis. Isaac Newton's famous work was published in the first edition of his *Principia*[2], which is generally recognised as one of the greatest of all record contributions to knowledge.

A *Multibody system* is a system that consists of solid bodies, or *links*, that are connected to each other by *joints* that restrict their relative motion. The study of *multibody dynamics* is the analysis of how such systems move under the influence of forces, also known as *forward* dynamics. Studies of the inverse problem, i.e. what forces are necessary to make the system move in a specific manner is known as *inverse* dynamics. This is particularly important in some branches of robotics where precise motion control is needed. While methods for analysis of elastic bodies are beginning to emerge, the *rigid body* is at the heart of most methods and applications. A rigid body is assumed to not undergo deformation when exposed to force fields. This is of course a simplification since no material can be applied with load changes without deforming. Nevertheless, for a large number of cases, considerable insight can be gained by modelling systems of rigid bodies.

For simulation of the dynamic behaviour of a mechanical system a large number of analysis tools have been developed which allow the automatic formulation and solving of the equations of motion by the computer for many types of mechanical systems. Computer code guidelines for simulation of multibody system dynamics are given in [37,38]. Mechanical engineering simulation software like ADAMS [39] and DADS [40] are commercial and have been around since the 70's. They form Newton-Euler or Lagrange equations of motion and integrate them numerically for given initial conditions. More recent software is Working Model [41] that provides a more intuitive modelling environment. The above systems all have the advantage of the possibility to visualise the calculated motions, giving a better understanding than from studying time histories.

[2] Principia (1687), revised by F. Cajori. University of California Press, 1934.

## 2 Aim and scope of research work

A computer-aided concurrent engineering system might look like Figure 1. The dashed line represents the focus area in this project.

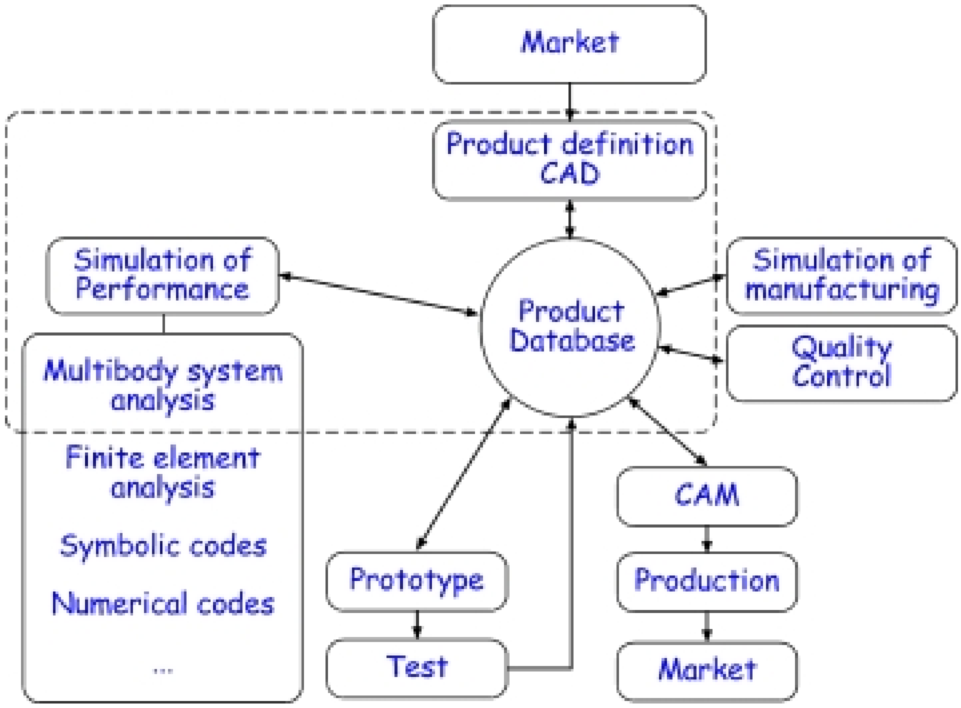


*Figure 1. The information flow in a computer-aided concurrent engineering system [42].*

The different tasks are performed at different stages of the development process although some tasks might be performed concurrently in an iterative process. As seen, the importance is in modelling and simulation of product performance, within product development.

The research question is formulated as:

*How can structuring of products, simulation models and their usage be made in order to make the process of computer aided simulation of dynamic mechanical systems more effective in the product development process?*

The possibilities and advantages of computer aided simulation of mechanical systems are not fully exploited in industry today and the industrial importance of achieving a more effective simulation process will lead to:

- Enhanced possibilities to analyse more design solutions.
- Improved possibilities to simulate more situations.
- Better quality through better base of decision.
- Shortened product development time through less iterations.

Scientifically, achieving the research goal will result in:

- Identification of phases that influences the effectivity of the simulation process.
- Thesis of how the structuring of the simulation process in product development can be made.
- Evaluation of the formulated thesis.
- Ability of implementation in other simulation processes of the product development process.

The research in this project is based on existing theories concerning product development processes and methods, concurrent engineering and multibody dynamics simulation.
Two axioms guide the development of this project;

**The approach has to be hardware independent**

Previous work to make simulation more effective has concentrated on developing *faster calculation* methods. Instead, this approach is to make the process of multibody dynamics more effective by *structuring products, simulation models and their usage.*

**The approach has to be demonstrated and evaluated in a realistic environment**

Perform studies of how computer aided simulation of dynamic behaviour is used within industry today. Use experiences from current process for multibody dynamic simulation. Apply experiences from structuring of products, Quality Function Deployment, Design For Manufacturing and Modular Function Deployment. Develop thesis. Test the thesis on real cases in co-operation with industry.

## 3 Multibody dynamics in the product development process

Traditionally, mainly large companies with special technical analysis departments have used simulation in their development of products. Due to the rapid development of digital computers, and since the techniques for modelling and simulation are becoming mature, industry is eager to use and implement them as tools into their development processes. Simulation is a necessary and effective tool for the company to use in order to make cost effective and secure decisions.

### 3.1 Simulation processes

An iterative generic product development process is shown in Figure 2. The smaller upper and lower arrows indicate some possible simulation processes during the development. These could be Computational Fluid Dynamics, Finite Element or Multibody Dynamic Analysis among others.

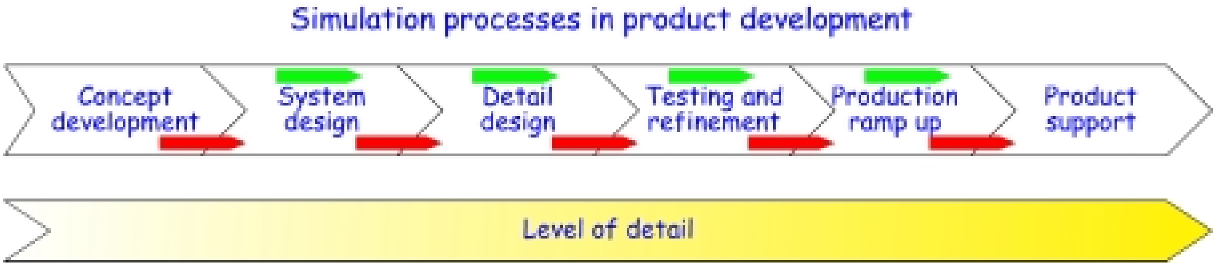


*Figure 2. Different types of simulation processes in product development.*

In Figure 3 a typical methodology for multibody dynamic analysis is extracted from the development process. During the lifecycle of a product the same questions arise several times, see the multibody dynamics simulation methodology in Figure 3. In the early stages fast modelling and comparative analyses are crucial in order to evaluate different concepts. The accessible information is often insufficient and unstructured and the time frame for decisions limited. At later stages the product is defined with higher level of detail, and accurate analyses are increasingly important. In these phases often better information is available in form of experimental data from prototype testing. This makes it possible to verify the developed simulation models. After this verification, the simulation model can be used to predict, with reasonable accuracy, the behaviour in other situations than the experimentally tested ones.

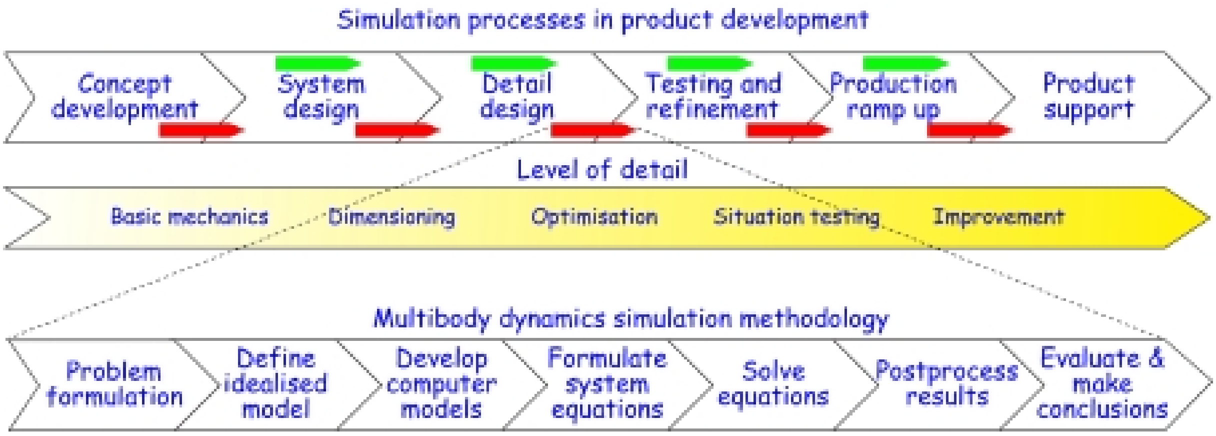


*Figure 3. Multibody dynamic simulation in different parts of the development process.*

Simulation involves the use of a methodology, see Figure 3. The methodology is similar independent of the level of detail of the model and the chosen simulation method. This makes it easier to reuse earlier work and easier to document the performed work.

The products are often complex and include many degrees of freedom as well as non-linear characteristics. This implies that it only occasionally is possible to find analytical solutions to the equations of motion. Often, one must use numerical experiments where the motion of the developed models is calculated for different situations. It is often suitable to connect the definition of the dynamic system to a CAD-tool, where it is relatively easy to define geometry, calculate mass and inertia, position of joints and loads etc. 3D CAD models are also suitable for investigation of aerodynamic forces, for visualisation of the design, and for animation of dynamic performance.

## 3.2 Mechanical system development

The development of a product is often an iterative process, both the whole process as well as underlying sub-processes. There are different aspects when developing a product regarding if it is a new mechanical system, original design, or if it is a redesign of an existing product, continuous design.

### 3.2.1 Original Design

When performing original development of a mechanical system it is advantageous to perform simulations in order to:

- Be able to make well-founded decisions early in the product development process.

  *By performing early analysis it is possible to try out basic design concepts without extensive prototype design.*
- Give the designer a possibility to test more ideas in shorter time.

  *With a digital model of the system it is easy to make changes. These changes would be very time consuming for a physical prototype. This implies a possibility to choose from more concepts which gives a better base for decisions* *and hereby a possibility to a better product solution. Parametric models can be used for design studies where simulations can be performed automatically until a desired target value is reached.*

- Separate the different design solutions.

  *One must clearly define the design, the assumptions and the evaluation criteria. By having to do this, the design originality is clearly stated.*
- Understand the product behaviour and how it is affected by different factors before it is manufactured.
- Discover unexpected behaviour.
- Be sure that the product fulfils the demands.

### 3.2.2 Continuous development

When dealing with continuous development of a mechanical system, simulations might be beneficial of the following reasons:

- In order to improve the product.

  *Many products have a long life cycle. There are financial incitements to continuously improve their performance. The issue is to use existing designs as far as possible as well as having well motivated arguments for making changes.*
- In order to optimise design solutions regarding for example wear, fuel consumption, weight and risk for accidents.

  *Here, the earlier product versions, and simulation models, are very useful when optimising parameters for the next product generation.*
- To estimate the product sensitivity to changes caused by, for example, weather, wear and ageing.
- To test unrealistic or dangerous situations as for example high speed running with trains.

  *The risk of product failure and hereby following consequences as person injuries, material damages, delays in traffic etc. makes it very expensive to test new ideas. Simulation ought to be used in order to make a reasonable judgement of the product performance in advance. The physical system parameters are used as input for the simulation model.*
- To understand the product behaviour and factors that effect the behaviour at controlled repeated conditions.

  *In full-scale field experiments many parameters vary at the same time, for example wind loads, temperatures, air humidity, vehicle conditions and infrastructure. By developing models and study effects of changes in different parameters during controlled conditions one can locate resources where they are most beneficial.*

### 3.3 Modular multibody dynamics modelling approach

When simulating, for example, catenary/pantograph dynamics in the development of a current collection system it is important to consider in what way the different methods are to be used. Generally, simulation departments have simulation experts that build, simulate and analyse results of given task given from, for example, the design department. In this way the special domain knowledge of the design department is lost since they do not perform simulations themselves. If the tools were handled in such a way that the simulation department developed a parameterised simulation model of, for example a pantograph suspension, and the suspension department designers were given this model, then they could combine their domain specific knowledge with the simulated behaviour and develop a good product. This approach would make parallel development of subsystem models, or simulation modules, possible. If the different developed subsystems then were integrated into a common simulation environment where total system simulation were performed it would be possible for the subsystem designer to see the impact of his development to the total system behaviour without having the knowledge to build the total system. Simulation models developed when working with pantograph/catenary systems might look like Figure 4.

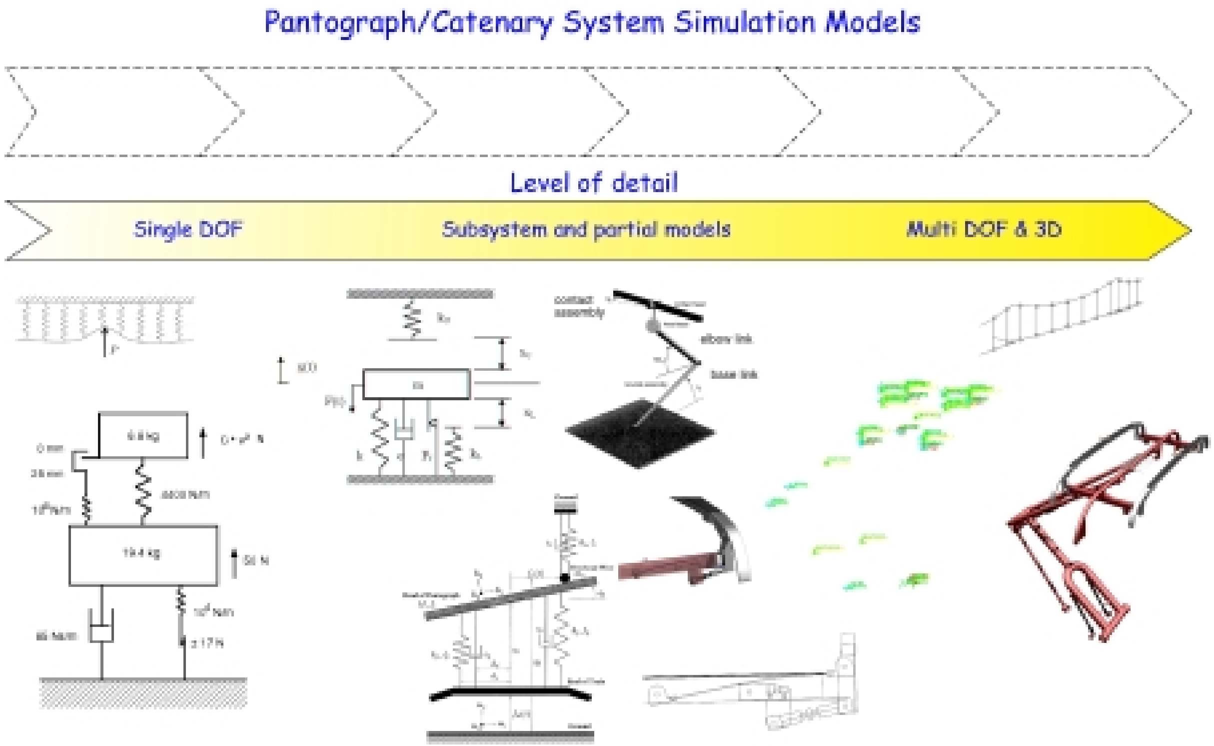


*Figure 4. Simulation models developed for pantograph/catenary system [43,44,45,46,47].*

By building the full system simulation model out of a library of subsystems many solutions would be possible. Each domain developer updates his one domain library. A catenary/pantograph simulation module environment could then look like Figure 5.

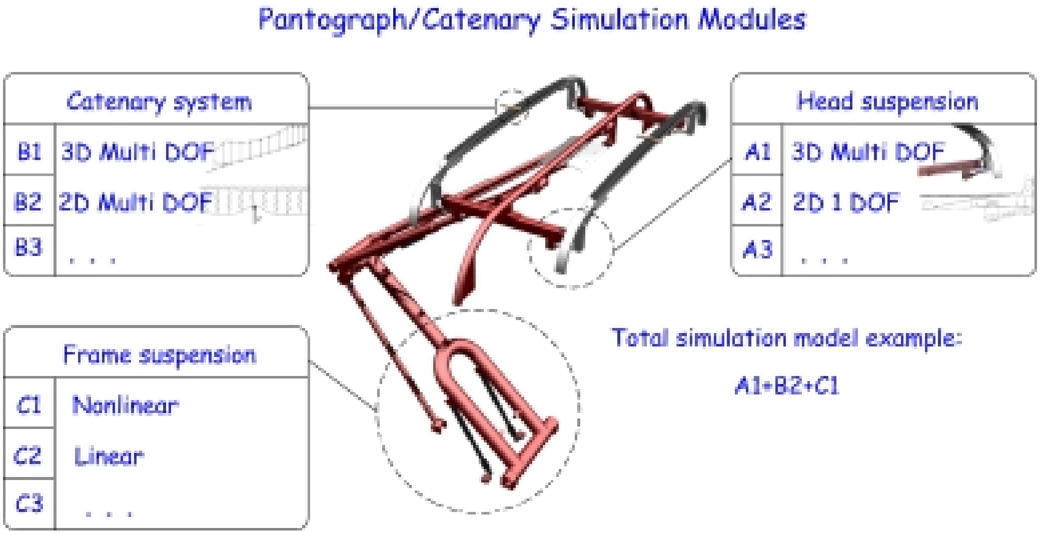


*Figure 5. Module system for pantograph/catenary system simulation.*

When developing the simulation models it is important to define the interfaces, or boundaries, of the model. Then every simulation model can be connected to the other simulation models later on in the process. The advantage of this approach is that the model consists of modules that are separated with specified interfaces which makes it possible to replace an old module with a newly developed one without changing the individual specification of the other modules. This creates the possibility to test different design solutions with as little effort as possible. The modular approach gives the opportunity to reduce time in the product development process and will make it easier to develop new generations of products. Other effects are that a design engineer and not only a simulation expert can develop simulation models and perform simulations.

### 3.4 Structuring of Modular Products

In terms of structuring the above mentioned models, or modules, the techniques from product structuring in general is observed. Ideally, the same module structure of a product should be used within the whole company; i.e. the engineer sees the same modules as the salesman, the manufacturing engineer, the development engineer etc. But, the development of modular structures of products is not an easy task. The different customer requirements that exist on a product in a modular product family may limit or prevent the modular approach. Product structure requirements within the company may also impose problems. Specially, a product that undergoes mainly simulation driven development, due to a high demand on performance rather than style, might have difficulties undergoing modularisation. One of the reasons to this is that the virtual modules used for simulation may not correspond to the physical modules of the product.

# 4 Summary of papers

## 4.1 Paper A

This paper describes the product development process at Indexator AB; a company developing hydraulic rotating joints for heavy lifting equipment. The paper describes the computer support and information flow within the engineering design department and related departments. The work demonstrates that the company has a clear view of its information flow and how computer aids are used in the different parts of the product development process. The advantage of using computer tools for design, analysis and planning is clearly seen. Lack of integration between different computer tools result in unnecessary regeneration of product information at different stages of the development process. The integration problem is mainly due to the unplanned development of communication and information flow concerning the design process.

## 4.2 Paper B

In this work the Modular Function Deployment (MFD) method is used to structure a product family of rotators for heavy equipment. The MFD method is used with two different point-of-views corresponding to the differences between the assembly department and the development department. The main differences of these two departments' demands are due to the way the product is developed. The assembly department has a tendency to develop a manufacture oriented design, and the development department develops a design more based on computer simulations. The aim is to identify differences and similarities of the modular structure resulting from the two objectives. Problems when structuring simulation models using the MFD-method are identified. It is shown that the two structures are very different and there are needs of additional evaluation factors in the MFD method in order to account for the implementation of modularisation with respect to dynamic analysis.

## 4.3 Paper C

This paper concerns modelling and simulation of the pantograph/catenary interaction in a current collection system for trains. Main interest is how the dynamic behaviour of the system is effected by changes in the characteristics of the pantograph head suspension and how the system can be modelled. The methodology of multibody dynamics is used when modelling the system. Parameter variations are determined by measurements on full-scale pantographs subjected to different wear situations. The methodology of factorial design is used for planning of the numerical simulations. The dynamic analysis shows that viscous damping and friction are the most important parameters. The dynamic range of the contact force between pantograph and catenary increases with speed. It is shown that the proposed methodology has proven to be a valuable tool when investigating the effects of different wear situations on the dynamic behaviour of a pantograph. The results can be used to evaluate maintenance criteria for pantographs.

# 5 Conclusions

This work describes simulation of multibody dynamic systems in the product development process. The papers presented describe how computer tools are used in product development and how multibody dynamic analysis can be applied to high-speed train pantograph/catenary systems and rotators.

How computer based analysis tools are used today is shown in Paper A in relation to a company's product development process. An efficient product development process is a crucial task for manufacturing companies. Evolving company specific strategies can only be achieved by introduction of an effective project organisation and simultaneous engineering strategies in product development, production, sales, customer service etc. One way to deal with this is to use a modular approach to the products. There are some methods to develop good choices of modules from a manufacturing point of view. In Paper B, the Modular Function Deployment (MFD) method is used to structure a product family. The method is used with two different point-of-views corresponding to the differences between the assembly department and the development department. Problems when structuring simulation models using the MFD-method are identified. It is shown that the two structures are very different and there are needs of additional evaluation factors in the MFD method in order to perform modularisation with respect to dynamic analysis.

The usage of and methodology for advanced dynamic analysis is addressed in Paper C. This paper give an insight in multibody system dynamics and the type of problems that are solvable with this methodology. Clearly, the implementation and integration of such a specialised discipline into the product development process requires large efforts in terms of making the method easier to use.

The development of the simulation models in Paper C and the product structuring of Paper B is beneficial when developing a prototype system for a modular simulation environment.

The work concentrates on simulations of multibody mechanical systems with different levels of abstraction, treated as modules. An outcome of achieving this is an increased modelling flexibility and shortened lead-time.

The work is performed in co-operation with industry and tested on real cases and results are implemented continuously in the co-operating companies.

## 5.1 Further work

There are some interesting questions that have arisen during this work. The main issues are:

- How to define, structure and use simulation modules in an effective way?
- What simulation model is to be used and how shall it be developed?
- What tools should one use to analyse the model?
- When is the right time to start simulating?
- How is it possible to develop simulation models in parallel?

A way to answer these questions is to continue the work presented in this thesis by developing a method for using multibody dynamics in development of mechanical systems, with a structured approach. The building, implementation and evaluation of such a design system is of high interest as well. The work performed in Paper A is top level work on the broad area of product development while the work in Paper B is related to structuring of products as well as simulation. Paper C illustrates analysis of dynamic systems. The task of bringing the two traditionally separated areas of product development and dynamic analysis is a real challenge. By doing this a more effective product development can be achieved as well as a more effective simulation process.

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