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MULTI-DOMAIN SIMULATIONS INTRODUCED IN PRODUCT DEVELOPMENT PROCESS

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ABSTRACT
Computer-based modelling and simulation assists in developing an idea into a product and in the improvement of the properties of the existing product. This improves the competitive ability of the company and shortens the path of new innovations from the idea to the market. Increasing requirements for existing products calls for e.g. environmental-friendliness, cost-orientation and adaptability. Using modelling and simulation it is possible to improve product life cycle cost and usability. This paper describes results of the project that included development of simulation-based design process and particularly application of computer simulation tools and methods on this process.
This research studies improvement of simulation-based product development models with a standardized IDEF0-flowchart. IDEF0-flowchart is a standardized, purpose-built tool for modelling decisions, functions and actions in an organisation or a system. At first, six widely recognised product development process models were chosen as the basis of the research. In next stage, a series of interviews of design project leaders were carried out in five different Finnish companies manufacturing mobile working machines, and the present practise of product development process was presented. Thereafter, the simulation-based product development process was modelled. The large case study with the real product model data of a mobile working machine gave input to the simulation-based product development process model.

Keywords: Simulation-based design, product development, IDEF0

1 INTRODUCTION
Modelling and simulation are becoming more common in the development of products and systems. Products are more complex. Managing and optimising the overall solution is becoming increasingly important. It should be possible to combine all factors essential to operation in a simulation: mechanics, actuators, control systems, active components and structures, user impact etc. on the system to be analysed.
However, simulation-based product development can be very challenging for organizations. This is due to the many new techniques required in order to bring a product development process to a new level. Information and new ideas must be created, examined, processed, tested, and transferred to organizations.
This paper describes results of the research project 'Simulation-based design process of smart machines'. The basic idea of the project was that the simultaneous design of different technical processes is inevitable in order to develop modern, optimized products. The project had three principal themes: simulation-based design, control of machine reliability and operability and the interaction between these two. In this paper we are focusing on one sub-project that included development of simulation-based design process and particularly application of computer simulation tools and methods on this process.

1.1 The need for the improvement of the design process
The actual elaboration of the product development process was first touched on in the 1920's, but it took thirty years for the first suggestions for the systematic methodologies for designing products to be published. The first actual methodologies for the product development, which were published in 1965, were Hansen's Konstruktionssystematik [1]. As early as in this methodology, the product development

project was divided into clear and distinct phases. The following step was taken in the 1980's and several design process models were presented [2, 3, 4, 5, 6, 7]. These methods presented the product development as an algorithm, in which the goal was generally to improve product development. Later 1990's product development (PD) design process models were extended to cover production, quality and economy issues and tools to control the above-mentioned issues were also connected to the models [8,9,10,11]. The most significant trends during the last few years for the design process model has been NPD (New product development), see for example [12]. NPD-based process models emphasise customer-orientation and thus these models emphasised consumer products. However, the content of the actual design process phases has not really changed from what they were in the models of the 1980's.

The applicability of PD process models has been criticised because a universally applicable path or order of activities which could be used as such in all the product development projects does not exist. Instead, the theory models can be used as reference models from which suitable items are brought into use and supplemented by specific tools according to an enterprise's field of business [2]. A reason for the minor adapting of PD process models is that the improvement concentrates on the introduction of new tools, such as the CAD, CAM and CAE, and the PD process model itself is not perceived as the subject of the development. Also, there is a lack of people at the management level who would have time to study the newest research results and adapt them in practise. The persons who work in product development are bound up with designing products, so they do not have time to go into the PD process itself. Characteristic of the design work are several overlapping projects and hard schedule pressures. The customers and the management of the company wait for the immediate reaction to new demands and to the emerging problems [17]. Furthermore, the product process improvement does not show any direct advantage, as in for example the introduction of new design software tools, f.ex. CAD-system with new features.

The significance of the uniform PD process model, however, will increase when the product development enlarges to contain the whole product life cycle. When manufacturing, maintenance, supplementary services, recycling, etc. are considered, the scope of the product development will increase and at the same time its controllability will become more difficult. The distribution of product development work between partners has the same effect. Many subcontractors bear the responsibility for the sub-assemblies made by them. If "PD process model dictionary" is missing, controlling the product development is difficult. Uniform methods ease the control of the product development management.

The problem in the big companies is to find a PD process model which is simultaneously practical and universally applicable enough. Furthermore, there should be an advantage from the use of the model to the project leaders, as well as to the designers, so that it will be implemented.

The main objective is to improve the effectiveness of the product development process when product simulations are utilized. The sub-objectives are:

- to develop methods for discussing the product development process in a systematic way,
- identify what possible problems the simulation based product process brings out in the product development,
- to secure as efficient utilisation as possible of different product simulations and
- to improve product development in which the simulation tools are integrated to the whole life cycle of the product.

2 PRESENT PRACTICES OF THE STUDIED COMPANIES

This research studied product development process models using standardised flowchart, The Integrated Definition for Process Modelling (IDEF0) [13]. It is a graphical representation of a process that exhibits the activities and their interdependence that make up the process to any desired level of

detail. An activity model reveals the interactions between activities in terms of inputs and outputs while showing the controls placed on each activity and the types of resources assigned to each activity.
At first, six widely recognised theoretical product development (PD) process models were studied: the Systematic Approach of Pahl and Beitz [15], Generic Product Process of Ulrich and Eppinger [11], Pugh's Total Design [9], Integrated Product Design of Andreasen [2], Suh's Axiomatic Design [10], and TRIZ [14]. These six models were the basis for a reference model that was used as a communication tool in interviews with the product development project leaders of five different companies. The generic PD process model was composed after interviews. The generic model describes the current product development practise in these companies. In next stage, it was created a new simulation-intensive PD process model according to the knowledge gathered during the main project and background knowledge of modern computer simulation tools and methods.
Theoretical product development process models, the reference PD model, the generic PD process model and the simulation-based PD process model were represented using IDEF0. A reason to employ IDEF0 as the modelling tool is its simplicity and good experiences of it in the same type of projects.
The product development process used in industry is divided into six phases (Figure 1). The first phase is the business process, where business cases are investigated and technology development projects or product development projects are launched. In a technology development process activity, new technologies and components are researched and the technology information collected in this phase is transferred to the conceptualisation phase, or back to the business process activity as information.

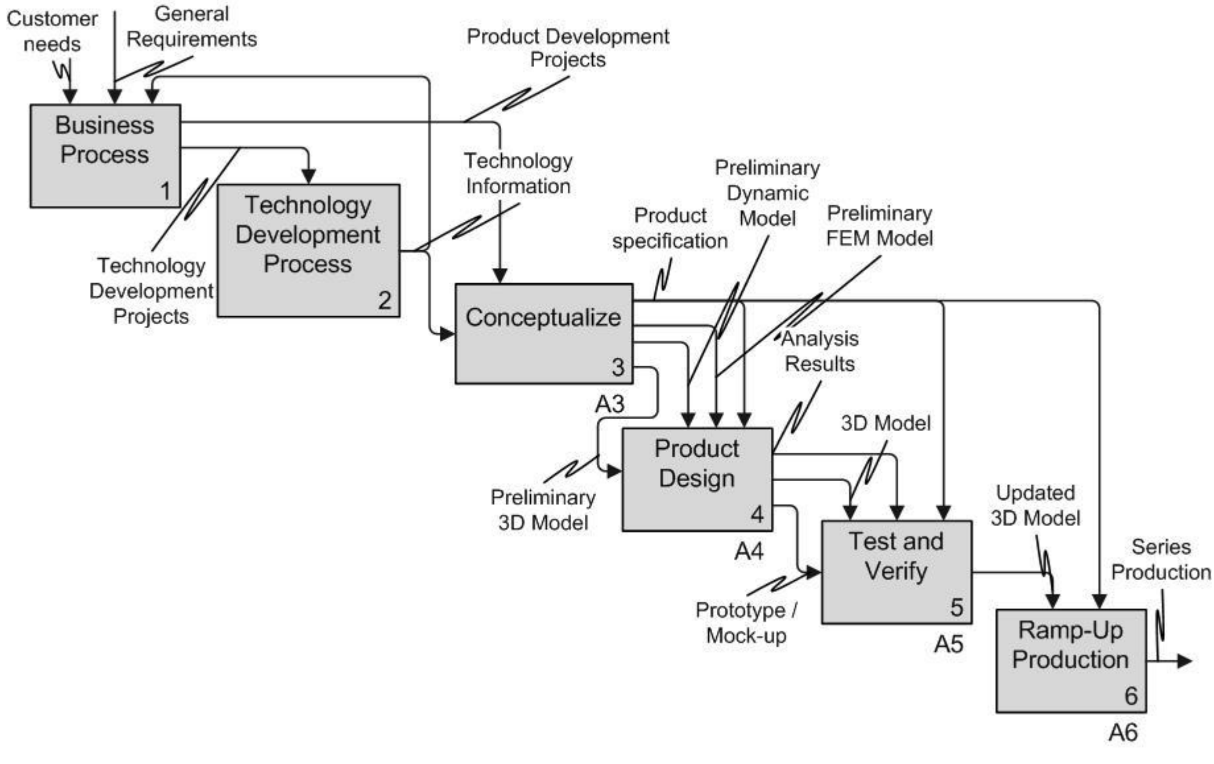

Figure 1. The present practice of product development used in industry is divided into six phases.

In the conceptualisation phase, the preliminary 3D-CAD model of the product is created and the first simulation tests are carried out. The principal solution of the product is outlined by making the simple 3D models and carrying out preliminary dynamic and structural analyses. The load information needed in the structural analyses is obtained as the results of dynamic analyses. The concept sharpens up iterating between modelling and the analyses to the level in which the coarse 3D model of the product exists. The model contains all components and subsystems which are essential from the point of view of functionality, but details like chamfers have not been designed. In a very iterative manner, the concept is finalised and the product design phase begins.
In the product design phase, the preliminary CAD-models are detailed with iterative cycles of simulation, tests and redesigning. All the parts and components are designed in detail, iterating between the 3D modelling and dynamic and structural analyses. The building of the prototypes of the

whole product or part of it, or of different mock-up models is begun when the design of the product has proceeded to a sufficient level to build the models in question.

After suitable results have been obtained from the tests, the simulations are verified by the means of prototype tests. The tests are performed according to the testing plan. The purpose of the tests is to make sure that the product meets the demands of the specification: for example operating characteristics, serviceability and performance. The results of the prototype tests are compared with the results of analyses that have been done at the product design phase. If there are significant differences between the real tests and the analysis results, the input parameters of analysis methods or methods themselves have to be explored for future needs. The design errors that have been perceived in the prototype tests are corrected, the necessary parts or components are designed again and the changes are updated in the 3D model. Prototype tests are carried out with the renewed parts to the extent necessary. Redesign and testing are performed until the demands of the product specification are met.

The necessary changes to the product are made and production is ramped up. The verification results are also used to update the simulation tools to make them more accurate.

3 SIMULATION-BASED DESIGN PROCESS

Simulation-based product development can be very challenging for organisations. This is due to the many new techniques required in order to bring the product development process to a new level. Information and new ideas must be created, examined, processed, tested, and transferred to organisations.

An analysis activity may seem to be performed ad hoc, but it is always based on a lot of experience and careful consideration [16]. The reason for conducting a modeling and simulation activity is always a request to determine what behaviour a specific product or part of a product shows in a specific situation. A general description of the analysis activity is given in IDEF0 notation in Figure 2.

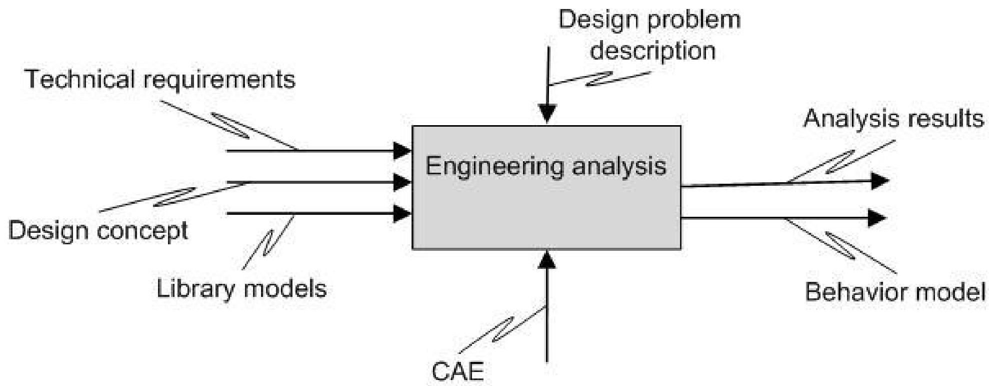

Figure 2. A general description of the analysis activity.

The description in Figure 2 says that the engineering analysis activity has three input sources; a design concept, technical requirements and library models. Library models are prepared and stored models of some or all parts of the design concept. The design problem description is a control mechanism that will give the scope of the analysis, and CAE refers to the mechanism or tool that will assist the activity. As a result of this activity, we will reach a behaviour model of the actual system and numerical results from a given set of boundary conditions.

The presented simulation-based design process consists of six phases (Figure 3). The input of the process is customer needs and the output of the process is the product launch. The two first phases remain the same as in the present practise of studied companies.

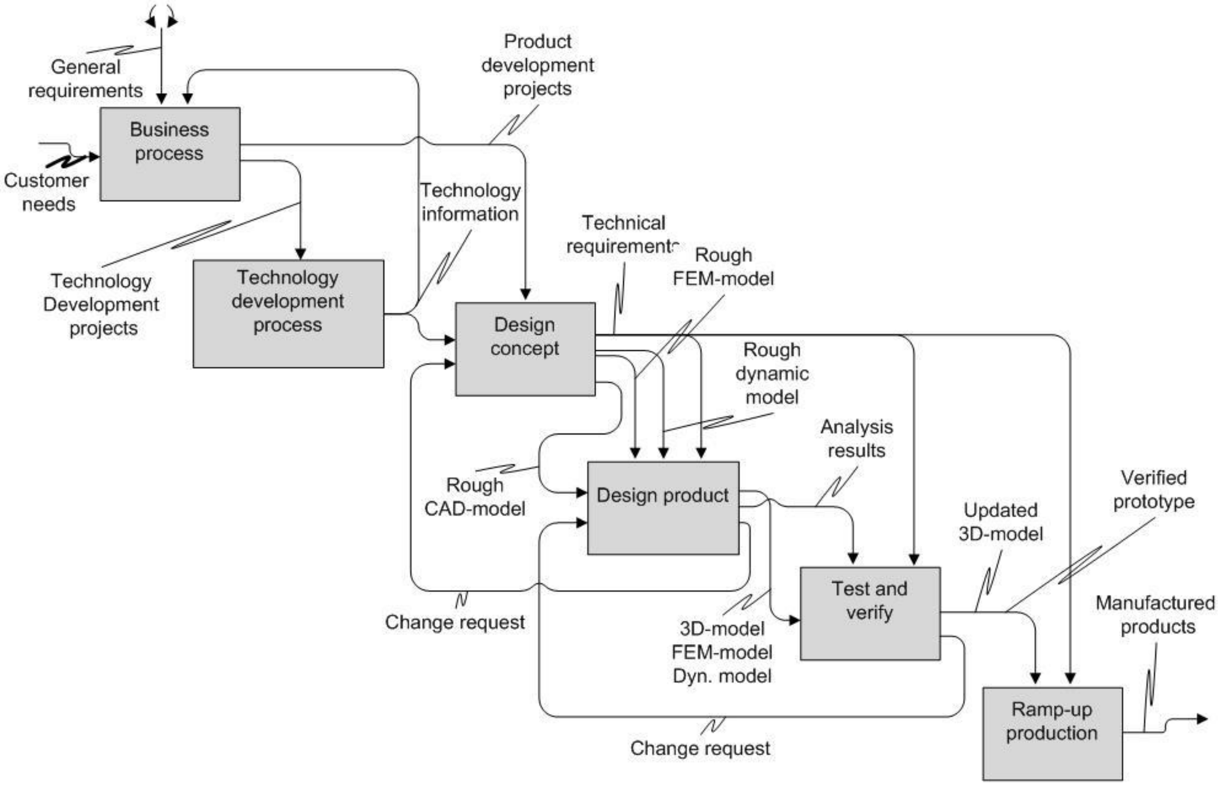

Figure 3. The simulation-based product development process model. The topmost level includes six phases.

3.1 Design Concept

In the design concept phase, the technical requirements are identified, and they control establishing function structures for the input for making rough CAD-models (Figure 4). In this context, the CAD-model comprises components and assemblies. The rough CAD-model is a simple representation of the product, and can be basic 3D solids, such as blocks and spheres. Rough CAD models are utilised in analysing spatial constraints ("Analyse kinematics"), simulate strength and dynamic behaviour. Strength and dynamic simulation results, such as displacements, stress, strain, acceleration and velocity are analysed to evaluate different design concepts. In this phase, alternative product concepts are generated and evaluated, and a single concept is selected for further development. A concept is a description of the form, function, and features of a product and is usually accompanied by a set of specifications, an analysis of competitive products, and an economic justification of the product development project.

In the concept phase, dynamic analyses using the coarse method are performed. The suitability of the mechanical design may be assessed using dynamic and strength simulation techniques. A CAD model of the concept is generated and dynamic analyses can be performed. A dynamic simulation is performed to assess e.g. dynamic loads on a mechanical structure. The structural finite element model (FEM) parameters may be utilised in order to consider flexibility issues. Dynamic loads on a component may reveal structural deformation, which can be eliminated through modification of the mechanical design (Figure 5).

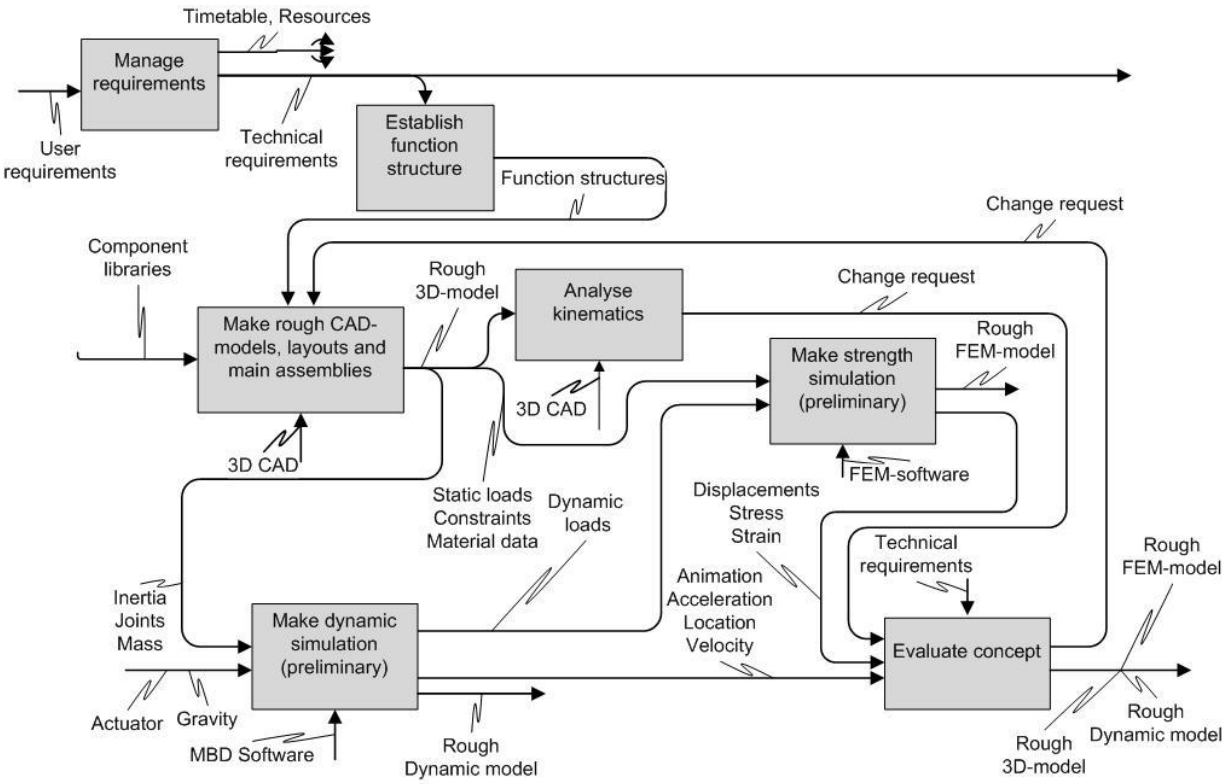

Figure 4. The design concept phase.

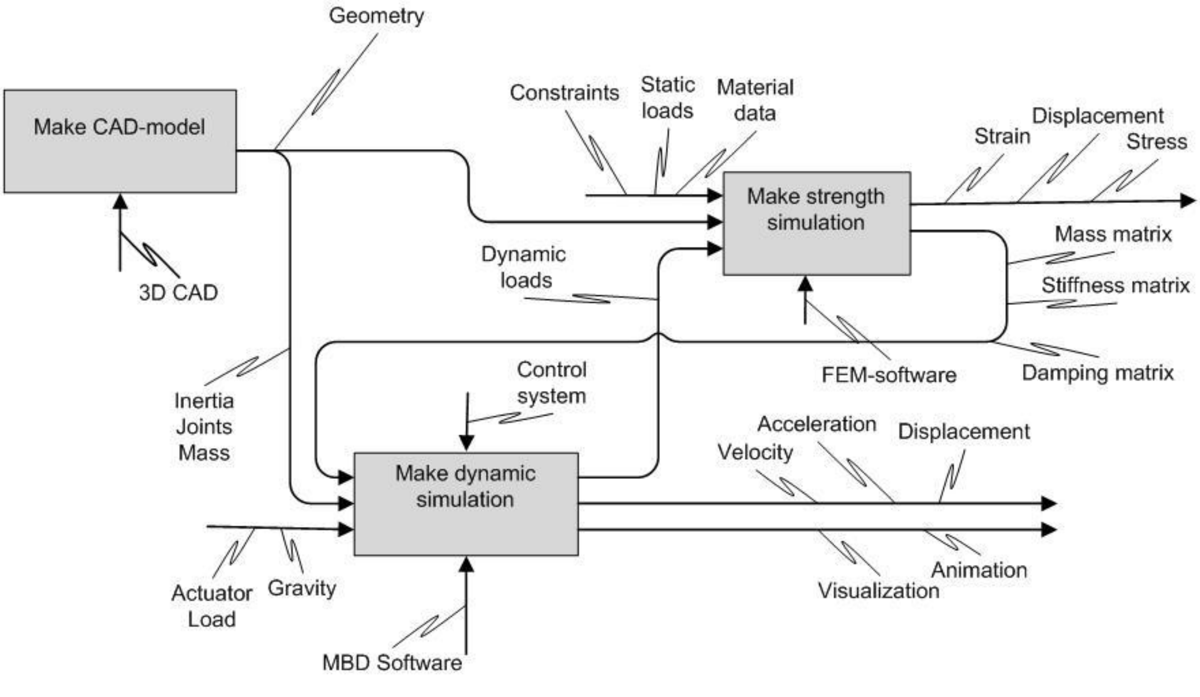

Figure 5. The dynamic simulation loop.

3.2 DESIGN PRODUCT

The design product phase (Figure 6) includes the definition of the detailed 3D model, which includes the product architecture and the division of the product into subsystems and components. Dynamic simulation may utilise component libraries, and as the 3D-model has evolved, real-like mass, inertia and joint locations are even being used. Strength simulation can also be computed at a detailed level and stresses and strains can be used to estimate fatigue life. In the design product phase, a light real-

time simulator model can be created and ways to simulate and assess human performance, safety and comfort in work places like mobile machines and vehicles can also be discovered.
The output of this phase is the complete specification of the geometry, materials, and tolerances of all of the unique parts in the product, the identification of all of the standard parts to be purchased from suppliers, and a detailed 3D-model for fabrication purposes.

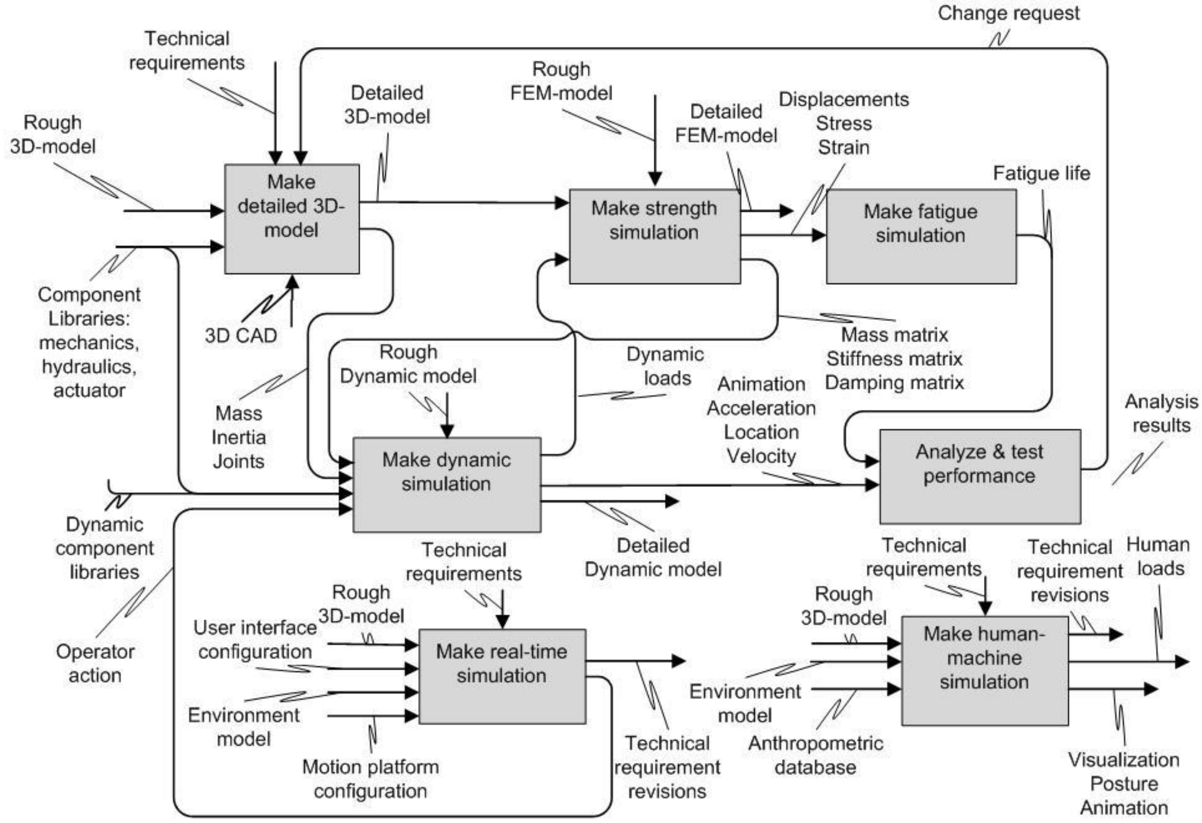

Figure 6. Design product phase.

The primary goals for the usage of real-time simulators are to reduce product development cost and time by design optimisation. Putting real-time simulation technologies into practical usage in the engineering field has always been an interesting goal within the research community. The performance limit of computing hardware and the efficiency of software algorithms are critical obstacles in this field. Additionally, real-time simulation environments are complicated systems consisting of different engineering disciplines.
One of the challenges of using real-time simulation as part of the design process is to produce the necessary systems set-ups fast enough so that the process is not delayed. The simulation results need to be available well before important design decisions have to be made.
Real-time simulators can be used in the product development to help to define various physical properties, functional characteristics and performance of the product in virtual world. In the product definition phase and in concept design, accurate behaviour is usually less important. Instead, virtual mock-ups with simplified functionality may be used (Figure 7).

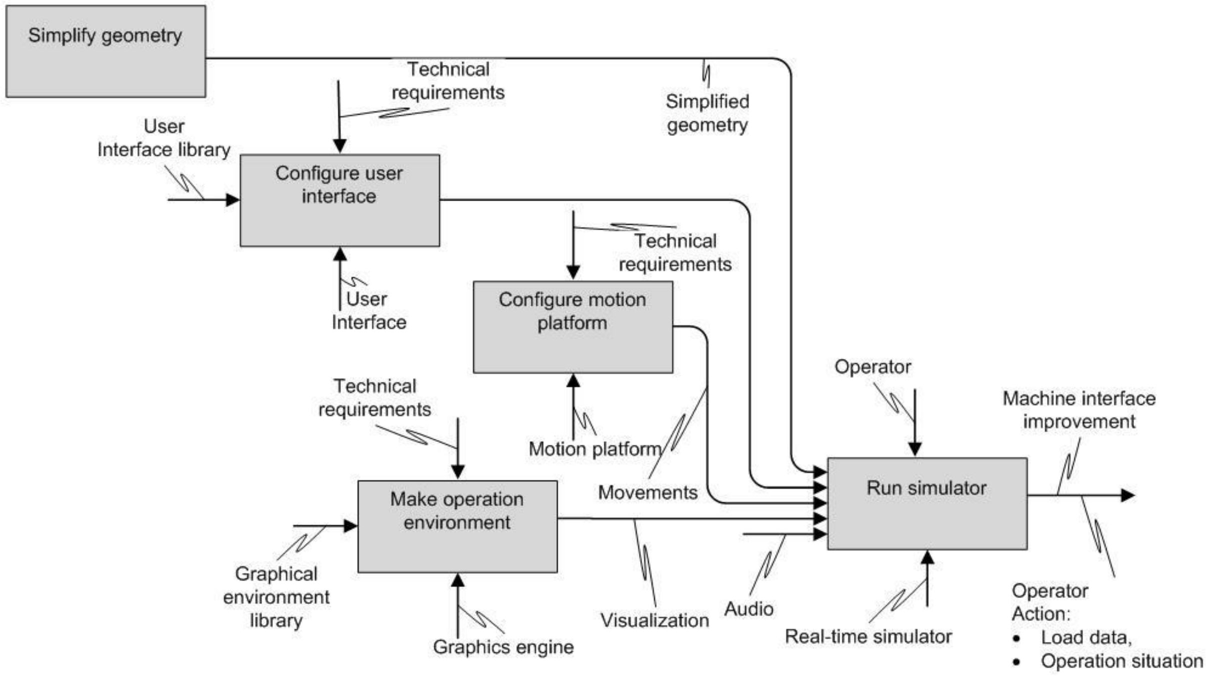

Figure 7. Real-time simulation in the design product phase.

During the product development, one of the main concerns of a design engineer is the fatigue life. When estimating fatigue life the major parameters are stress/strain values under dynamic load history and material parameters. In addition, environmental conditions are crucial for fatigue life computation. The determination of stresses and strains using the finite element method (FEM) is common practise in many companies. FEM has broad applicability to different types of analyses (deformations, stress, plasticity, stability, vibration, impact, fracture etc.), as well as to different classes of structures, e.g. shells, trusses, frames and components like gears, bearings, and shafts. Several methods have been developed for estimating the fatigue life of components, e.g. S-N curves, ε-N curves or crack growth, and their suitability is considered case-by case (Figure 8).

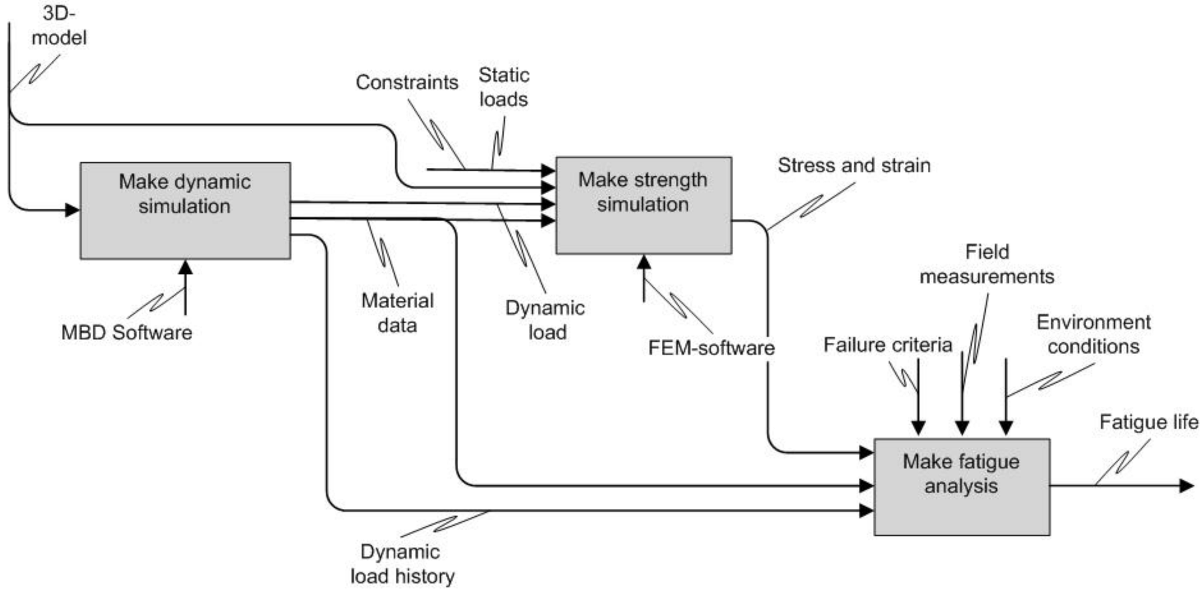

Figure 8. Fatigue analysis in design product phase.

From the point of view of a human as an operator, product development demands a knowledge of the human being his- or herself, and of his or her relationship with the environment. The product development needs to be able to cover the whole system, instead of being restricted to a product. Product developers have to comprehend the whole field of human work. This means that 3D models and simulation are needed to identify human physical needs in a working environment. Simulation provides possibilities for collaborative design.

In the design concept phase, specifying the technical requirements for the product or system is a major task. For human-centered design, it is essential to extend these technical requirements to better include human physical needs. For example, these include comfort, safety, health, and effective work task performance.

Human-operator simulation uses 3D-models, the biomechanical model and the environment model. The human model is composed of rigid segments that are connected using joints and forces. The conventional type of controllers or spring-dampers of applied human models do not seem to be the best possible way of simulating human actions accurately in many scenarios and applications. The use of soft computing (i.e., fuzzy logic, neural networks and genetic algorithms) offers more satisfactory possibilities for simulating human motion control (Figure 9).

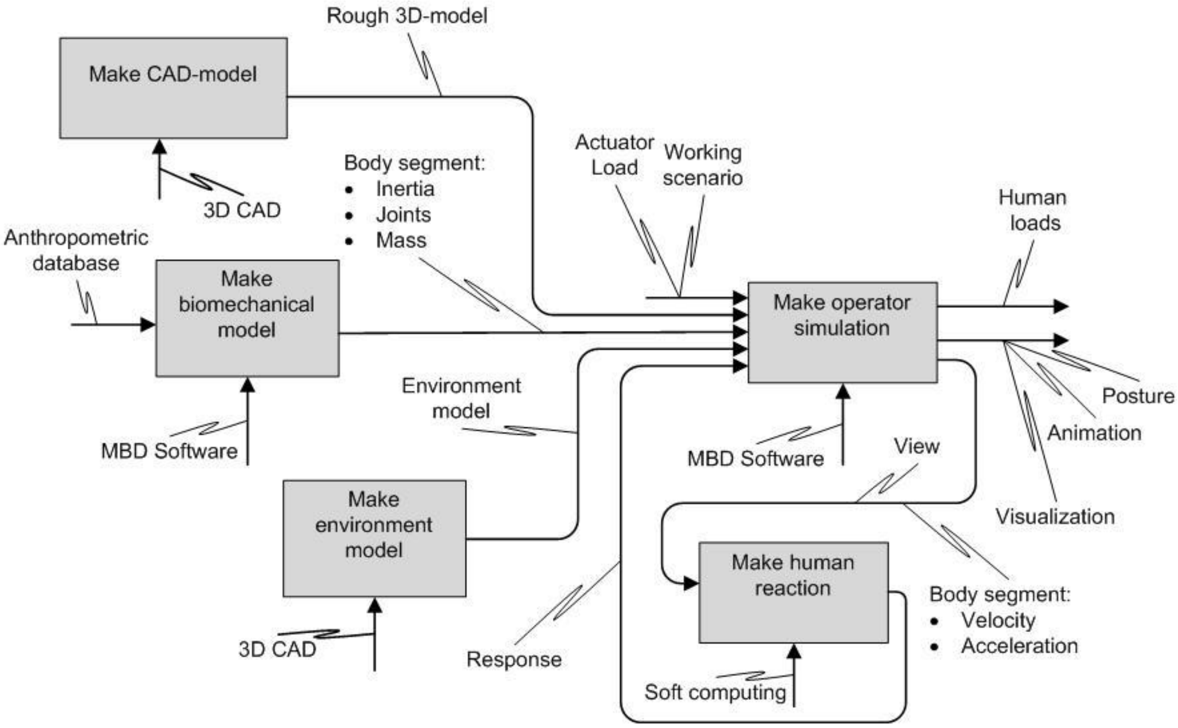

Figure 9. Human-machine interaction in the design product phase.

3.3 Test and verify

The test and verify phase involves the construction and evaluation of virtual and physical prototypes. Early prototypes are usually built with production intent parts, parts with the same geometry and material properties as those intended for the production version of the product but not necessarily fabricated with the actual processes to be used in production. Prototypes are tested to determine whether or not the product will work as designed and whether or not the product satisfies the key customer needs. An important issue is to update the digital models using results from testing (Figure 10).

3.4 Ramp-up production

In the production ramp-up phase, the product is made using the intended production system. Fabrication simulation is performed to produce instructions for CNC-machines etc. Production simulation offers features that simulate the complex movement of equipment such as robots, machine tools, transfer lines, and special machinery. Factory simulation software features are also used to define the physical layout of manufacturing, material handling, and distribution systems. The purpose of the ramp-up is to work out any remaining problems in the production processes. The artefacts produced during production ramp-up are sometimes supplied to preferred customers and are carefully evaluated to identify any remaining flaws. The transition from production ramp-up to ongoing production is usually gradual and continuous (Figure 11).

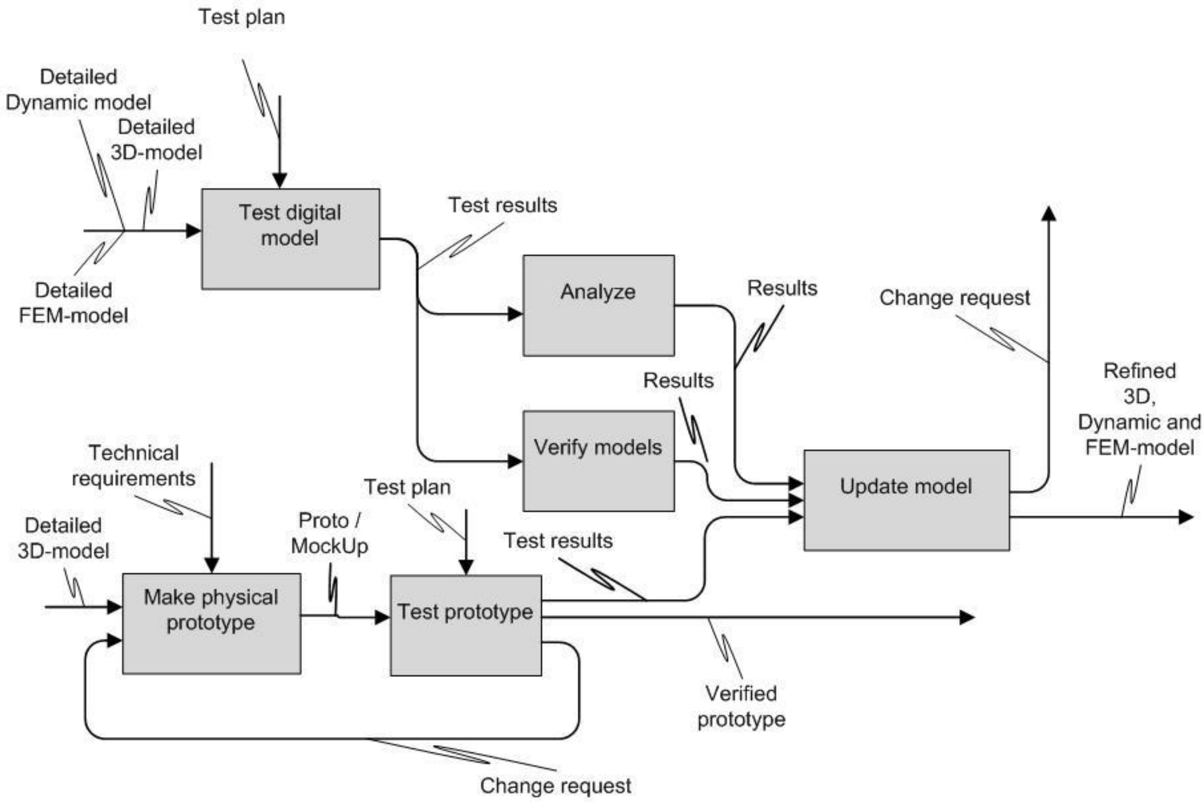

Figure 10. The test and verify phase.

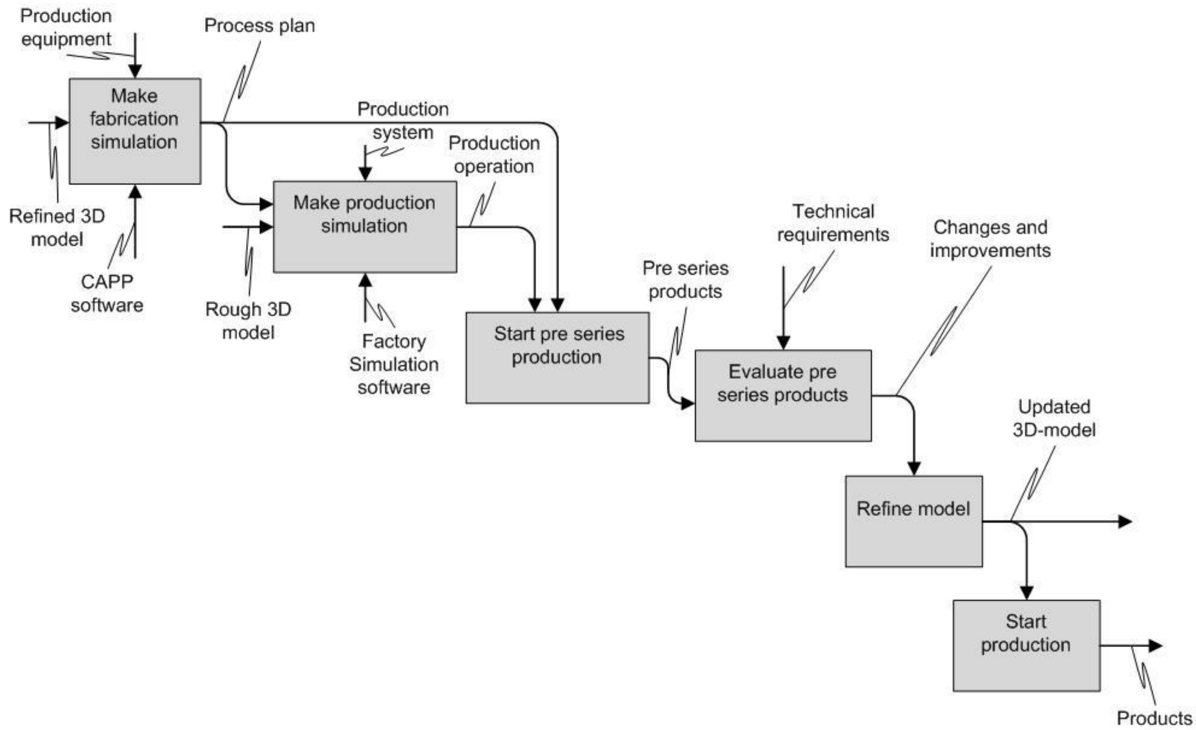

Figure 11. The ramp-up production phase.

4 CONCLUSIONS

The usage of simulation methods belong to modern product development. The advantages which are gained from the simulation are manifold: expensive and time-consuming prototypes and the number of the tests decrease, the properties of the products improve, the time which is used for making products shortens and the quality standard of products rises. Computer based modeling and simulation assists developing an idea into a product. This improves the competitive ability of the company and shortens the path of new innovations from the idea to the market.

The product development theories found in the literature were quite similar, but they differ from the product development practise used in companies. The process used in companies includes less tools (e.g. for innovating) and is usually more focused on gathering technological information and administrating ongoing development projects than theoretical product development process models.

The new simulation-based product development process emphasises more detailed description of design activities than the current practice. In the design concept phase the simulation activities are performed using rough models and the main task is to generate and evaluate feasible concepts so that technical requirements are met. Product properties are studied on a conceptual level and possible system elements are connected. Traditionally during the concept design phase many alternative designs were sought, usually without regards for their value and quality. In a simulation-based product development process model, the alternative concepts are quantified and therefore the best concept is selected for further development.

In the design product phase, real-time and human-machine interface simulation is introduced to product development. 3D-models are detailed and dynamic and strength simulations are performed. Fatigue simulation comes into picture. In the past, analysis of individual components was carried out by using prototypes and if a part failed then it was redesigned, manufactured and tested again

The test and verify phase involves the construction and evaluation of virtual and physical prototypes. Prototypes are tested to determine whether or not the product will work as designed and whether or not the product satisfies the customer's key needs.

In the production ramp-up phase, the product is made using the intended production system. Fabrication simulation is performed to produce instructions manufacturing. Additionally, factory simulation software features are used to define the physical layout of manufacturing, material handling, and distribution systems. The purpose of the ramp-up is to work out any remaining problems in the production processes. The transition from production ramp-up to ongoing production is usually gradual and continuous.

The large case study with the real product model data of a mobile working machine gave input to the simulation-based product development process model. Having the case study simulation model as a common platform to test ideas and concepts in practise influenced a lot especially to integrate dynamic simulation, real-time simulation and human–machine simulation into the new product development process model presented in this paper.

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