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# SIMULATION MODELS FOR MATERIAL HANDLING EQUIPMENT DESIGN – EVALUATION CRITERIA, METHODS AND APPLICATION

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***Abstract:*** *Decisive criteria for the efficient use of CAE are available and well proven but are focusing on engineering in general. These decisive criteria are hardly being transferred to Intralogistics. A CAE application method out of a pool of engineering tools of the Institute of Logistics Engineering TU Graz (ITL) tries to close this gap. In the application field logistics engineering the method assigns simulation tools by usage criteria to engineering phase methods and their design principles. This method can contribute to spread CAE and to lower application effort. The authors depict this method, give an exemplarily use and illustrate the benefit by two different simulation models (use cases) in two different application fields of logistics engineering.*

***Key words:*** *CAE methods, CAE selection process, logistics engineering, material flow systems, multi – body simulation, conveying systems, intralogistics, parcel handling.*

## 1. INTRODUCTION

The use of simulation models for structural and motion behaviour (CAE) for virtual product development is well known and accepted in different industries. High investment costs, high skills of users, difficult identification of application fields and a large amount of powerful simulation tools provoke obstacles for using CAE. Decisive criteria for the efficient use of CAE are available and well proven but are focusing on engineering in general. These decisive criteria are hardly being transferred to Intralogistics. VDI 2209 [1] informs only about the simulation method in a general way and not about the simulation tools. Standards and guidelines in logistics dealing with simulation are connected to material flow simulation (throughput) [36] and are not connected to engineering tasks and CAE therein. A CAE application method out of a pool of engineering tools of the Institute for Logistics Engineering TU Graz (ITL) tries to close this gap (Fig. 2 and 3). With regard to application in logistics engineering the method assigns simulation tools and provides usage criteria assigned to engineering phases. By a process driven selection this method contributes to spread CAE and to lower application effort especially in logistics engineering.

## 2. SIMULATION – METHODS AND DECISION PROCESSES

During the design processes in logistics engineering different tasks request various demands on CAE methods. Simultaneously with the progressive process steps the level of knowledge rises and so do input variables and boundary conditions of the CAE tools. As depicted in Tab.1 a variety of simulation methods and tools are available to power the engineering process. But broadly varying input factors and boundaries lead to different results and contributions so the tools have to be used target oriented to gain efficiency in engineering.

The aim of the introduced method is to gain a linkage between general CAE engineering expertise and special material flow engineering design issues concerning the following aspects:

- Usage criteria and requirements for CAE.
- Selection criteria to find the most practicable simulation method.
- The capability of the tools in design support for components and machinery.
- To clarify and assign calculation and simulation methods to design phases.
- Overview about commercial available simulation tools.

To structure the mechanical design process VDI 2221 is well known and established [2]. Fig.1 shows different tasks with CAE and assigns them to VDI 2221 design process. Additionally VDI 2211 [9] allows to structure CAE and simulation methods of structural and dynamic behaviour of technical bodies by effort and calculation power into three different classes. There are:

1. A-methods: are highly specialized in advanced programming languages and highly mathematical.
2. B-methods: are mostly commercially available software tools as stand-alone solutions (see list of methods in Fig. 3).
3. C-methods: are "quick-and-dirty" simulation approaches [37] in CAD-integrated environment or even less powerful analytical methods, derived from

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empiric knowledge (mostly field tests, sometimes CAE-testing).

It is now essential one time, to choose the appropriate method from A-, B- and C-methods to describe physical behaviour appropriate. But it is also essential to assign possible use of CAE to design phases and to identify its main purpose/benefit. Within ongoing research and a Habilitation thesis [8] methods were developed to properly choose CAD-methods for engineering tasks in logistics engineering[1] . Within one thematic field of "engineering for logistics" – methods for simulation and calculation – method B1 (MeB1) supports mostly unexperienced users in the decision process for CAE and the selection of the appropriate method. Main goals of MeB1 are:

- Dissemination of best-practice and use of various CAE techniques.
- Bring insights in:
  - Scopes of use and boundaries of CAE.
  - How various commercial CAE-tools fit common logistics engineering tasks.
- Introduce the most powerful and adequate tools. This is done by a process depicted in Fig. 2 and by a check-table (Fig. 3) which contains:
  - View in parallel of recommended use of CAE during design phases from various standards and guidelines.
  - Assignment of CAE-use to four phase design process in detail (compared to **Fig. 1**Fig. 1).
  - Assignment of commercial CAE-tools to design phases and principles of CAE (FEM, MBD, DEM).
  - Assignment of successful CAE-implementation and use in practice and assignment to common engineering tasks in logistics engineering.

[1] Some more methods and the identifying process of appropriate methods were also introduced in ICMaS'16 [35].

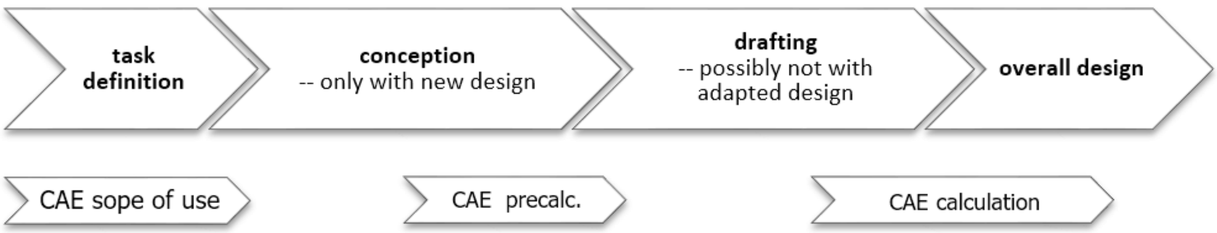



**Fig. 1.** CAE tasks in four phases of engineering design (according to VDI 2221 [2]).

*Table 1*

CAE-**tools and their successful application in and for logistics engineering – parallel view**

<table>
<tr><th colspan="2">Classification according to simulation method</th><th colspan="2">Classification according to VDI 2211 [9]</th></tr>
<tr><td rowspan="2">CAD-embedded simulation tools:</td><td rowspan="2">Many tools are very similar. Within the branch of CAD-embedded simulation tools exist for example:<br>• CS: Pro/ENGINEER, Creo Simulate (Mechanica, Mechanismus, Simulate)[10]<br>• SolidWorks (COSMOSWorks) [11]<br>• NX (once UG: Nastran) [12]<br>• CATIA (SIMULIA) [13]<br>• SimDesigner (Structure, Motion) operation of SimXpert-Templates[14]</td><td>C-Method:</td><td>• M: derivation of C-methods to model dynamics of chain hoists [22], [23] from B-methods</td></tr>
<tr><td rowspan="4">B-Method:</td><td rowspan="4">• Library of models „Technical Logistics“[24]<br>• M: master the behaviour of parcel flow and parcel dynamics in bulk [6]<br>• M: master the resonance phenomenon on chain hoists [25]<br>• M: master the drive system dynamics of horizontal carousel storage systems [26]<br>• E: master the polygon effect on chain sprockets [27]<br>• E: master the dynamics of electrical isolator strings in overhead mounted power lines (wire-ropes) [28], [29]</td></tr>
<tr><td>FEM:</td><td>• AW: Ansys and Ansys Workbench Platform [14]</td></tr>
<tr><td rowspan="2">MBS:</td><td>signalflow-based:<br>• SX: SimulationX [16]<br>• MS: MATLAB/Simulink [17]</td></tr>
<tr><td>geometry-orientated:<br>• AD: MSC ADAMS [18]<br>• RD: RecurDyn [19]</td></tr>
<tr><td>DEM:</td><td>• ED: EDEM [20]<br>• LI: LIGGGHTS [21]</td><td rowspan="2">A-Method:</td><td rowspan="2">• M: master the feeding process of parcels on sorting systems [30]<br>• M: master the behaviour of parcel flow [31], [32]<br>• M: master the dynamics of storage and automated storage/retrieval systems[33]<br>• M: dynamical effects to users on forklifts [34]</td></tr>
<tr><td colspan="2">Depending on engineering object size <u>(material flow machinery)- indicators:</u><br>M…machinery level<br>E….component level</td></tr>
</table>

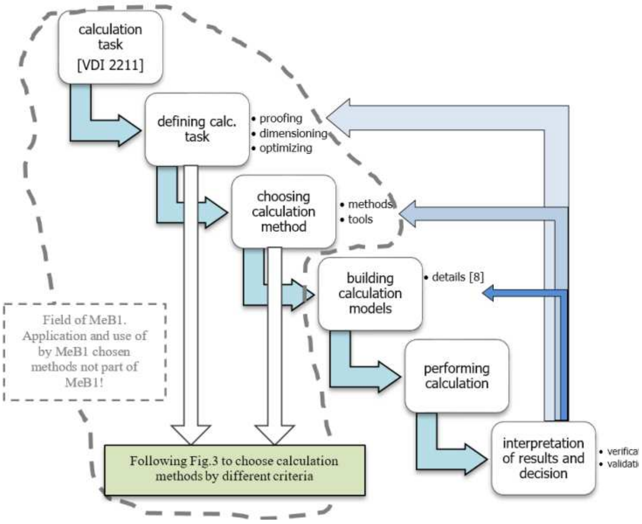



**Fig. 2**. MeB1 selection process for adequate simulation methods.

The CAE selection process of MeB1 starts by specifying the calculation/simulation problem clearly (Fig. 2). Following there is a clarification of calculation use for proofing, dimensioning or optimizing with calculation an engineering task. Here a first iteration starts. By choosing the appropriate method Fig. 3 comes into account as well as in the step before – one more iteration cycle starts. By building the right model (powering knowledge in [8]) the calculation is actually done followed by essential steps of validation and verification which can start several further iterations. Tab.1 accordingly explains best fitted (from experiences to be fully listed in [8]) CAE simulation-tools. Further, it describes fields of application and examples in concrete with successful use.

| | | | | | Application 1 | | Application 2 | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| **approach to design with VDI 2221 [1]** | **phase** | | **task definition** | **conception** | | **drafting** | | **overall design** | | |
| | **stages** | | 1. clarify and define task | 2. determine functions and their structure | 3. search for solution principles - combinations | 4. search for solution principles - combinations | 5. develop layout of key modules | 6. complete overall layout | 7. prepare operation and production instructions | |
| | **results** | | specificatoins | function structures | principle solutions | module structures | preliminary layouts | definite layouts | product documents | |
| **kind of design** | **new design** | | | | | | | | | |
| | **adapted design** | | | | | | | | | |
| | **variant design** | | | | | | | | | |
| | **repeated design** | | | | | | | | | |
| **methodological use of knowledge** | | | | | | | | | | |
| **CAE application after:** | | | | | | | | | | |
| **[VDI 2221]: as analysis and target** | | | | | + | | + | + | + (after MEK2) | |
| **[VDI 2221]: as integr. method f. optimization** | | | | | | | o | o | o | |
| **[VDI 2223]: computer-aided work equipment for the design** | | | | | Create principle solutions (pre-calculation) | Analyze principles solutions (recalculate) | | | | |
| **[VDI 2211]: Calculation and CAE** | | | | | | | Designing: Rule of the thumb, simple calcul. | | | |
| | | | | | | | | Optimization | | |
| | | | | | | | | | Recalculation, after change in construction a. empirical formula invalid | |
| **Application of the CAE for:** | | | Components, Assemblies, Machines, Systems | | | | | | | **Notation** |
| **Calculation** | **Structural mechanics** | | | | C, A | | C, A | C, A | | C...Components, A...Assemblies, M...Machines, S...Systems |
| | **Dynamics** | | | | A | | A, M | A, M | | |
| **Visualization (Dynamics)** | | | | | | | | A, M | | Demo3D for A. |
| **CAE-Methods by required time [VDI 2211]:** | | | | | | | | | | |
| Class | Example | Product | | | | | | | | |
| **A**- Academic | multi-domain, nonlinear,... | advanced programming language, MS, programs advanced B-Systems | avoid in design process - develop B-Methods from it , assessment separately: Support through MeB3! | | | | | | | not part of the standard engineering education |
| **B**-Bridge builder | stand-alone Tool | AD, RD, SX, AW, CS, LI, ED | | | o | | o | + | | |
| | | | Designer delegated, wide knowledge necessary, assessment separately. | | | | | | | |
| **C**-Common | CAD-embedded o. empricial formula | CS, empirical-analytical calculation standards | | | + | | + | o | | A: best quality and maximum time required, C: opposed to A. |
| | | | Designer does it alone - preferable! Empricial formula (Design pattern of the conveyor technology), assessment included: Support through MeB2! | | | | | | | |
| **CAE-Methods by principle und product:** | | | | | | | | | | AD: MSC ADAMS, RD:RecurDyn, SX: SimX, MS: MATLAB/Simulink, AW: Ansys Workbench, CS:Creo.Simulate, LI: LIGGGHTS, ED:EDEM. |
| **FEM** | | | | | CS | | CS, AW | AW | | |
| **MBS** | | | | | AD, RD | | AD, RD | AD, RD, SX, MS | CS | |
| **MBS-AS** | | | | | SX,MS | | SX,MS | SX, MS | | |
| **DEM** | | | | | LI, ED | | LI, ED | LI, ED | | |
| **CAE-Methods by issue:** | | | | | | | | | | MBS f. FEM: Allocation dynamic loads and loading conditions for Load combinations in FEM-Calculations. |
| **Master the nonlinear materials** | | | | | (FEM) | | FEM | FEM | | |
| **High cycle fatigue calculation** | | | | | | | | MBS f. Cons.f. | | |
| **Avoid oscillations** | | | | | MBS | | | MBS (FEM) | | |
| **Lightweight design** | | | | | | | (FEM) | FEM | | |
| **Optimize function** | | | | | MBS | | MBS | MBS, FEM, DEM | | |
| **Increase safety** | | | | | | | | MBS f. FEM | | |
| **Master the sound propagation** | | | | | | | | MBS f. FEM | | |

**Fig. 3.** CAE Application Method for Material Flow Systems Engineering "MeB1" – applications Chap. 3.1, 3.2 highlighted.

## 3. TWO APPLICATIONS OF SIMULATION IN LOGISTICS ENGINEERING

In the following chapter, the authors are going to present two application scenarios of proper CAE methods and their benefit.

### 3.1. Application 1: Validation of singulation principles for parcels in bulk

The increasing amount of parcels in the CEP-market (courier, express and parcel services) causes a higher need for efficient processes in distribution centres (DC). According to [7], function areas within a DC are structured in feeding, preparation, identification, sortation and discharging areas. To increase the overall efficiency of the distribution a consistent automation of the linked processes is a feasible solution approach. While most core processes in a DC like identification, conveying and sorting can be fulfilled in a highly automated and efficient way, loading and unloading processes are mostly done by manual operation. Especially the feeding process, that can be divided up in unloading, singulation and transfer, at the beginning of the distribution processes is mainly important and often a bottleneck.

The solution approaches to automate the feeding process show two tendencies in parcel handling: Via robotics and via treatment as a bulk material [5]. Within the research fields of the ITL in Graz, the description of parcel and unit load behaviour as a bulk material is investigated [4–6].

By taking in account that parcels get unloaded via automated process, the unloading and singulation process appear separately and so they have to be investigated. In the following we concentrate on the illustration of the singulation process.

Starting with parcels in a 3D bulk, the singulation can be structured in 3D/2D and 2D/1D sub steps. For each of these steps a few active principles are known as promising (Fig. 4).

Within the engineering process of singulation, the evaluation of usage criteria and effectiveness of the singulation principles is an essential task. The systematic development approach of VDI 2221 [2] classifies this process to the engineering phase "conception", in order to compose the singulation modules to a tailored system by considering a specific singulation application . In the light of the large amount of singulation principles and the fact that test plants are expensive, simulation models are a practicable way to compare different solution principles and combinations. To simulate the interaction and contact behaviour of independent bodies, multibody (MBD) and discrete element method simulations (DEM) are suitable. As research results of the ITL illustrated [4], DEM is the most efficient method to simulate the behaviour of a large amount of parcels in bulk.

The calculation task now is to model the behaviour of parcels in bulk by various singulation principles to evaluate the singulation effects. After defining the calculation task, the CAE application method (Fig.3) leads to the tools "LIGGGHTS" and "EDEM" by taking design step and calculation task into account. By taking acquisition costs into consideration the DEM simulation models are put into practice with the open source tool "LIGGGHTS".

To evaluate effectiveness of the singulation principles "sequential acceleration", "inclined belt conveyor" and a combination of them, the simulation scenario depicted in Fig. 5 is developed.

In this scenario, the horizontal belt conveyor transports 50 parcels out of a container ($v_1$ = 0.01 m/s) and hands them over to an inclined belt conveyor that operates with higher conveying speed ($v_2$). Through the different acceleration of the belt conveyors, a 3D/2D singulation of the parcels in bulk is put into effect. At the end of the inclined belt conveyor, a virtual control area is defined to measure the singulation effect by counting the parcels that are still above each other (3D). To investigate influence parameters on the singulation process, the conveying speed ($v_2$), inclination angle and friction coefficient (parcel/belt contact) of the inclined belt conveyor are varied. The variation of these three parameters in steps of three different levels generates 27 different parameter combinations to be virtually tested [5].

As a main benefit of the simulation and virtual testing, the prove of effectiveness of singulation principles and the efficient evaluation of their parameters

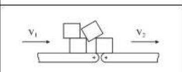
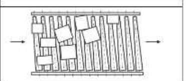
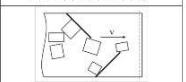
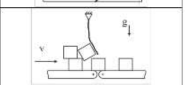
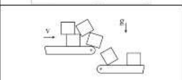
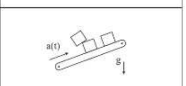
| operating principle | schematic diagram | dominant physical principle | | singulation dimension |
|---|---|---|---|---|
| sequential acceleration |  | surface force | friction force | 3D/2D |
| angled conical rollers |  | | | 2D/1D |
| stationary diverter |  | | normal force | 2D/1D |
| flexible barrier |  | | | 3D/2D |
| vertically shifted (belt-)conveyor |  | volume force (gravity, inertia) | | 3D/2D |
| inclined belt conveyor (accelerated) |  | | | |

**Fig. 4.** Active principles of parcel singulation [4].

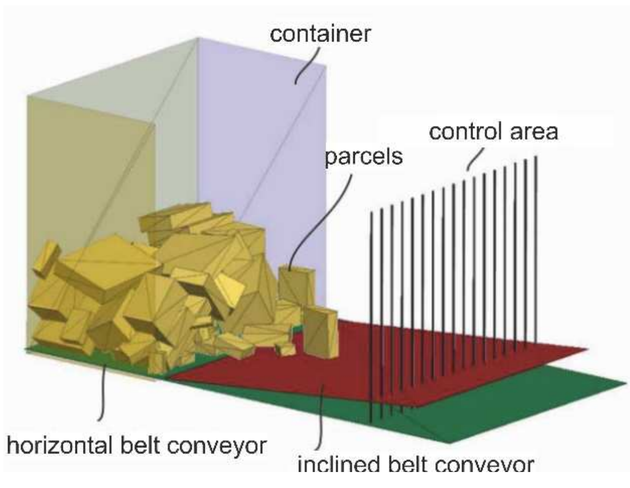



**Fig. 5.** Simulation scenario in "LIGGGHTS" to evaluate different singulation principles [5].

can be outlined. This led to a faster development of a prototype for automated parcel-unloading [5].

### 3.2. Application2: Design of belt conveyors by considering dynamical load states

Automated Material Flow Systems (MFS) are powerful components of most intralogistics systems. Within the group of steady conveying systems, belt conveyors are widely spread and operate in different load spectrums and conditions. For the design and automation process of belt conveyors, the dynamic behaviour of components, assemblies and systems has to be known well. According to the systematic design approach VDI 2221 [3] this process step is allocated to engineering phase 3 "drafting". To calculate the mechanical behaviour of the belt conveyor by operating in dynamical load states the dynamical reduced model (Fig. 6) and the corresponding equation system (in extracts Eq. 1-6) have to be solved.

Therefore, Newton's equations for translational and rotational motion are used.

The equation system according to the free body diagram of belt and the spring/damping element indexed 0 leads to Eq. 1:

$$m_{belt_{red0}} \cdot \ddot{x}_0 = F_{S_0} + F_{D_0} - S_{0x} - F_{FR_0}. \qquad (1)$$

The formulas for the subsystems take into consideration the reduced masses of belt $m_{belt\_red}$ and load unit $m_{LU\_red}$, the spring and damping forces $F_S$ and $F_D$, the belt forces $S_x$ and the friction forces $F_{FR}$ (contact belt/support).

The initial belt force $S_{0x}$ directly depends on the pretension force $F_{PT}$ (Eq.2)

$$S_{0x} = \frac{F_{PT}}{2}. \qquad (2)$$

Equation 3 sums up the subsystem consisting of unit load n − 1 and the according spring/damper elements n and $n-1$.

$$(m_{LU_{n-1}} + m_{belt_{redn-1}}) \cdot \ddot{x}_{n-1} = F_{S_n} + F_{D_n} - F_{S_{n-1}} - F_{D_{n-1}} - F_{FR_{LU_{n-1}}}. \qquad (3)$$

After inserting the coefficient of damping $d$ and spring stiffness $c$, Eq.3 forms to Eq.4.

$$(m_{LU_{n-1}} + m_{belt_{redn-1}}) \cdot \ddot{x}_{n-1} = c_n \cdot (x_n - x_{n-1}) + d_n \cdot (\dot{x}_n - \dot{x}_{n-1}) - (m_{LU_{n-1}} + m_{belt_{redn-1}}) \cdot g \cdot \mu - c_{n-1} \cdot (x_{n-1} - x_{n-2}) - d_{n-1} \cdot (\dot{x}_{n-1} - \dot{x}_{n-2}). \qquad (4)$$

Newton's equation for rotational motion and Eytelwein's law to describe the motion behaviour of the drive system lead to Eq.5:

$$J_{drive} \cdot \ddot{\varphi} = -T_{drive} + r \cdot S_{x_2} \cdot (e^{\mu\beta} - 1). \qquad (5)$$

In Eq. 5 $\mu$ represents the friction coefficient of the contact belt/drive drum, $\beta$ the wrap angle and $T_{drive}$ the drive torque.

Finally, Eq. 6 sums up the equation of translational motion of the slack side:

$$m_{belt_{slack}} \cdot \ddot{x}_{slack} = -F_{S_{slack}} - F_{D_{slack}} + S_{slack\_x}. \quad (6)$$

By taking different drive system specifications (synchronous/asynchronous) and operation modes (regulated/unregulated power up) in consideration (that leads to non-linear characteristics of $T_{drive}$ in Eq. 5, the exact solution of the equation system at dynamical load states is complex and mainly inflexible for further additions. To model the dynamical behaviour of mechanical systems the use of multibody simulation (MBS) is expedient. MBS methods can be divided up in two groups according to the model structure: geometry based orientation and signal flow orientation. Geometry orientated models take the shape of bodies in account so that boundary conditions can be affixed on the object's surface. The bodies interact with others via contact models. These object based MBS model are well suitable to model contact behaviour and to optimize details within a mechanical system. Signal flow oriented models replace the geometry-based bodies with their mechanical and material properties like mass, inertia, stiffness and damping and link the bodies with coordination functions or reduced models like spring/damper to simulate their transmission behaviour. So this simulation method is mainly more practicable to model the behaviour of larger systems and their interaction.

According to the CAE application method (Fig. 3) a few suitable MBS tools to optimize functions in construction phase "drafting" are outlined. By taking in consideration that the dynamic behaviour of the whole system "belt conveyor" has to be modelled, signal flow orientated models are identified as more practicable. By following the CAE application method MeB1, the multibody simulation tool "Simulation X" is selected to solve the equation system and to model the belt conveyor (Fig. 7) by operating with an asynchronous drive system in unregulated power up mode.

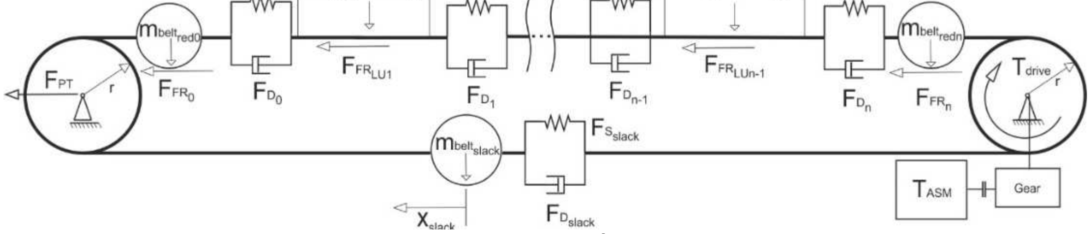


**Fig. 6.** Dynamic reduced model of a belt conveyor.

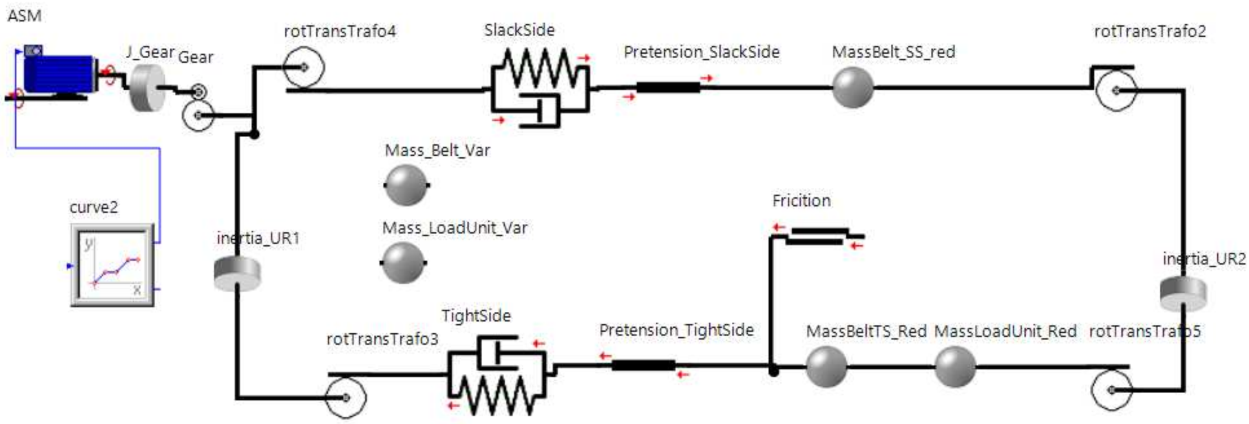



**Fig. 7.** ITI Simulation X model to calculate the dynamical behaviour of the belt conveyor.

As an outcome of the simulation model, the following results can be outlined:

- dynamical behaviour during transient states;
- the mechanical load of the drive system by operating in different dynamical load states;
- efficient dimensioning of the required pretension force and dynamic belt forces during operation;
- acceleration of the transported goods in stop-go operation.

Hence not only drives but the more components of the systems like the belt itself can be dimensioned properly by identifying load spectrums from simulation per cycle and in general. This leads to better dimensioning by considering operational stability.

Figure 8 exemplarily depicts as result the curves of dynamic belt forces at the load states standby (1, pretension force), the transient pulse because of unregulated power up cycle by an asynchronous motor (2), idle (3) and full load (4).

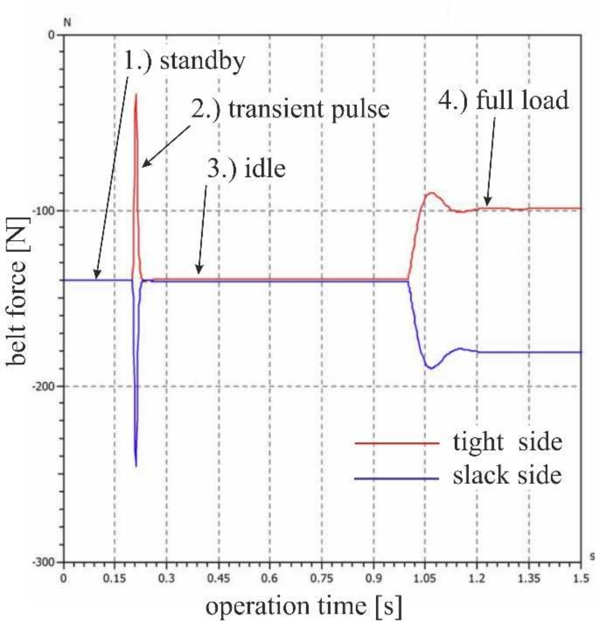



**Fig. 8.** Simulation results: curves of belt forces in tight and slack side at different dynamical load states.

## 4. RESULTS AND CONLUSION

One result presented is the method MeB1 to identify the proper simulation method corresponding to the engineering phase in context of the requirements in logistics engineering. It is stated that their future use will help the logistics industry to streamline simulation use and remove fear of contact. As further results the two applications depicted and their simulation models outline successful use of simulation and benefits with insights into detailed modelling supported by the large number of references provided.

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