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Approaches to Chain Drive Design Using Numerical Simulation

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ABSTRACT

The increasing integration of retail and Direct-to-Consumer (D2C) models has significantly increased the importance of pouch sorters in intralogistics. The centerpiece of these systems is the chain drive. Calculating the forces acting on the chain is complicated due to the large-scale construction and the numerous interacting components. A major challenge in determining the chain forces from the different subsystems lies in accounting for dynamic processes such as startup procedures, pouch oscillations, deviations from ideal operation and geometry, and emergency stops. Current calculation methods rely on quasi-static approaches and empirically derived coefficients that inadequately represent or completely ignore these dynamic processes. This paper addresses these issues by first analyzing the current calculation methods for this problem and then exploring the potential for knowledge transfer from other areas of mechanical engineering. The second part focuses on depicting system dynamics through numerical simulations. The numerical models used in this process are challenging to handle due to the high modeling effort and complexity. Thus, the paper presents approaches to manage this complexity. The results highlight the gap between current and required calculation capabilities. Numerical simulations demonstrate how this discrepancy can be bridged. The developed complexity management approaches provide valuable insights for further research, which will be pursued in a Ph.D. thesis.

KEYWORDS MBS (Multi-body simulation), Multibody Dynamics (MBD), System Simulation, numerical simulation, overhead conveyor system, chain drive, complexity management

1. Introduction

The continuous progress of digitalization and globalization leads to the increasing integration of retail and Direct-to-Consumer (D2C) models [1], intensifying the demand for efficient and flexible intralogistics solutions. In this context, pouch sorter systems are gaining importance due to their ability for dynamic buffering, batch sortation, and sequencing [2]. The core component of the pouch sorter system is a chain drive, which not only transports the pouches within the system but also provides the necessary drive power for the integrated switches, enabling the infeeding and outfeeding of the pouches.

1.1. Problem description

The large-scale construction of pouch sorter systems leads to high dynamic demands due to the interaction of many components. Pouch sorter systems represent a very specific application of a chain drive. Conveyor lengths exceeding 30 meters[1] [1], with continuous chain lengths moving up to 10 000 freely swinging load carriers per hour [2], result in highly dynamic loads. This makes the calculation of chain forces[2] under real operating conditions extremely challenging. Current calculation methods in this area are largely based on quasi-static approaches and empirically determined correction factors [3–7]. However, these methods are insufficient to accurately represent dynamic processes such as startup procedures, oscillation of carriers and pouches, deviations from ideal operation, and emergency stop situations. This leads to inadequate system knowledge, often resulting in over-dimensioned systems [8], failing to meet the requirements for sustainability and energy efficiency in modern technical solutions.

1.2. Objective and procedure

The objective of this paper is to explore possibilities and potentials for improving the design of chain drives using numerical simulations. The application case examined is a pouch sorter system, from which further considerations for other chain drives can be derived. Initially, an analysis of the current methods for determining chain forces in pouch sorter systems is conducted to assess the state of the art and its limitations. Subsequently, the potential for knowledge transfer from other areas of mechanical engineering is investigated to identify improvement opportunities.

A major focus of the study lies in depicting the system dynamics, such as startup procedures, oscillation of carriers and pouches, and emergency stop situations, of such systems. Initial approaches to using numerical simulations in this area will be presented. Approaches developed to handle simulations with high modeling effort and associated complexity are presented.

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[1] Apart from the usual literature, the authors are also aware of significantly longer systems with center distances of up to 50 meters.

[2] Chain force is the force that acts along the links of a chain and is generated by the movement of the chain. This force is primarily understood as tensile force, as the chain is typically used in such applications to pull or move loads.

The results of this study contribute to the use of numerical simulations for depicting the system dynamics of chain drives, using the pouch sorter as an example. Furthermore, the developed complexity management approaches provide stimuli for further research, to be deepened within the framework of a Ph.D. thesis.

2. Initial Situation and Problem

This section provides an overview of the initial situation of methods for analyzing the loads on chains in pouch sorter systems. It includes an assignment of the occurring loads on the system (Section 2.1). Sections 2.2 to 2.4 describe the current methods for determining chain loads and highlight existing weaknesses and areas for improvement.

2.1. Occurring Loads in Pouch Sorter Systems

To evaluate the existing analysis methods, this section provides an overview of the loads in pouch sorter systems. The literature does not contain specific descriptions specifically related to pouch sorter systems. Therefore, literature from overhead conveyor technology, of which pouch sorters are a subset, serves as the foundation. The starting point is the loads listed in [8] and [9], currently considered in overhead conveyor technology. These consist of inertial forces and friction-induced loads in the traction element and carrying devices. Due to the quasi-static nature of current calculations, reaction forces from dynamic processes are not included. Thus, the dynamic reaction forces for the pouch sorter system were identified and summarized in Table 1. This list outlines the requirements for calculating the acting loads. These are based on empirical

Table 1: List of the Occurring Loads in Pouch Sorter Systems

Inertial Forces	**1T**	Centrifugal Forces
	2T	Startup, Braking or Emergency Stop
	3T	Variable Transport Mass - Infeed/Outfeed
Friction – Traction Element	**1RZ**	Increased Friction due to Oscillations of the Traction Element
	2RZ	Conveyor Chain/Guide Rail
	3RZ	Deflection Resistance
Friction – Load Carrying Device	**1RT**	Bearing Resistance
	2RT	Rolling Friction of Load Carriers
Dynamics – Real Operation Conditions	**1S**	Superposition of Rolling and Sliding Friction of Load Carriers
	2S	Oscillation of Load Carriers
	3S	Increased Traction Force due to Superimposed Oscillation
	4S	Constraint Forces due to Geometric Tolerances
	5S	Periodic Force Application – Switches, Pre-tensioning and Drive

Sections 2.2 through 2.4 present three different analysis methods, each evaluated to determine whether the requirements from Table 1 can be met or where gaps exist. It should be noted that the loads change depending on the geometry and spatial

configuration. This results, for example, in gradient resistance when overcoming inclines or increased friction in curved sections.

Figure 1 shows an assignment of the loads occurring in an exemplary pouch sorter system. The generic geometry of the pouch sorter is based on illustrations in [9]. To better follow the descriptions in this work, the figure is used for both the assignment of loads and a brief introduction and explanation of the terms. In a pouch sorter, individual goods are transported in load carriers, also known as pouches. The pouches are flexibly connected to the load-carrying devices, known as carriers. Each carrier has a pair of running wheels for support within the conveyor profile and is driven by the conveyor chain. The conveyor chain is specialized to provide positive power transmission to the carriers. The drive torque is transmitted to the conveyor chain through a drive sprocket at a drive station (shown on the left side of the figure). The conveyor chain is supported by sliding rails within the guide rails, which provide bearing surfaces for the chain links and guide the chain through the system. The carriers are loaded and unloaded at defined points along the layout using infeed and outfeed switches (indicated in the middle of the figure). [4]

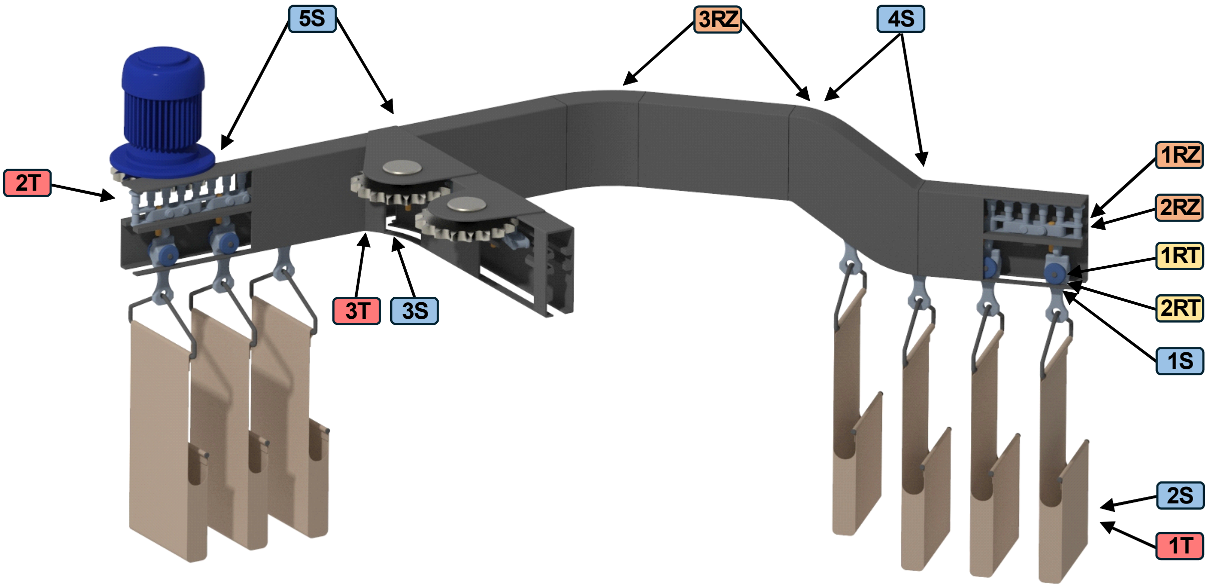

Figure 1: Allocation of the Occurring Loads in Pouch Sorter Systems

It should be noted that the respective loads are assigned to their origin in the figure. Naturally, the effects propagate throughout the entire system. "Increased Friction due to Oscillation of the Traction Element (1RZ)" is symbolically assigned to the chain. Increased friction due to oscillations can occur across the entire conveyor. "Deflection Resistance (3RZ)" is assigned to the horizontal as well as vertical curves of the conveyor layouts; it also occurs during the wrapping around the sprockets. "Increased Traction Force due to Superimposed Oscillation (3S)" is assigned to a switch in the middle of the figure. This involves the transmission of oscillations from two separately operated systems. But the superimposition of oscillations can also occur throughout the entire system. Carriers, drives, or tensioning devices can also introduce periodic forces into the system and trigger resonance. "Constraint Forces due to Geometric Tolerances (4S)" are assigned to the transitions between different conveyor profiles, as they most frequently occur due to misalignment. However, constraint forces due to geometric tolerances can also arise in other components of the system.

2.2. State of the Art - Calculation Methods for Determining Chain Force

This section provides an overview of the current calculation methods for determining loads in pouch sorter systems. Table 1 serves as the starting point, listing all the loads that occur in pouch sorter systems. Relevant literature[3] for the calculation of such systems is reviewed to identify existing calculation approaches for these loads and to highlight areas where further research is needed. The investigation is conducted from three different perspectives and is summarized in Table 2.

The first column of Table 2 addresses literature specifically focused on the loads in pouch sorter systems. Since no specific sources were found on this topic, this column refers to literature on overhead conveyor technology. This decision is based on the fact that pouch sorter systems are classified as a subcategory of overhead conveyors.

In the second column of Table 2 covers chains in conveyor technology in general. This literature describes calculations for systems with similar structures, such as scraper conveyors, trough chain conveyors, and bucket elevators.

The third column of Table 2 includes chains as general machine elements. This column is limited to roller chains and socket chains, as these are most frequently used as traction element in pouch sorters and therefore offer the greatest relevance for these systems. This column focuses on general calculation methods for chains.

It is important to note that all the mentioned sources exclusively conduct quasi-static analyses. Additionally, the calculations are performed with varying degrees of detail, leading to some loads being described only with correction factors or approximate formulas. Therefore the "Notes" column provides an overview of the level of detail. Fundamentally, the calculation of chain forces in all cited literature sources follows the same basic principle. Individual resistances of the components are determined and then summed starting from the sprocket of the drive. Recursive or iterative calculation methods are not applied.

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[3] The University Library of the Institute for Technical Logistics at Graz University of Technology served as the primary source for relevant technical literature. The focus was on the subject areas of conveyor technology and machine elements. Additional sources were accessed through the following platforms: ResearchGate, Google Scholar, Google Books, DTU FindIt, DART-Europe E-theses Portal, Academia.edu, and ChatGPT - Scholar GPT, using the search terms: Kettenantrieb, chain drive, overhead conveyor, circular conveyor, chain transmission, Steuerketten, roller chain, bush chain, sprocket chain, timing chain, control chain, and chain technology. The literature research was carried out in the period from January to June 2024.

Table 2: Assignment of Calculation Possibilities to the Literature

Source	Overhead Conveyor System	Chains in Conveyor Technique	Roller and Socked Chain as Machine Element	Note
Stetigförderer – F. Kurth [10]	3T 1RZ 2RZ 3RZ 1RT 2RT 5S	3T 1RZ 2RZ 3RZ 1RT 2RT 5S	3RZ	Consideration of increased friction due to oscillation chain force. Chain link resistance neglected. Coefficient for various operating conditions (contamination and unevenness of the rail track).
Stetigförderer Teil 2 – Gert Salzer [9]	1T 2T 3T 1RZ 2RZ 3RZ 1RT 2RT 2S 3S 5S	1T 2T 3T 1RZ 2RZ 3RZ 1RT 2RT 2S 3S 5S		External force introduction only through empirical coefficients. Takes into account oscillations and vibrations in the system – assumes that the elasticity of the overall system compensates for these (except for resonance).
Auslegung und Gestaltung von Antriebssystemen für Stückgut-Sortieranlagen – Will [8]		2T 3T 2RZ 3RZ 1RT 2RT 1S 5S		Ramp-up process calculated, from which the correction coefficient is derived.
Technisches Handbuch Logistik 1 – Wehking [11]		1RZ 2RZ 3RZ	1T 2T 1RZ 2RZ 3RZ 1S 5S	Calculation of the resistance with a coefficient for: friction-induced load, operational and impact coefficient. Dynamic chain force considered also through empirical coefficients.
Transport- und Lagerlogistik – Martin [7]		1RZ 2RZ 3RZ		Resistance calculation from traction drive is with an empirical coefficient. This coefficient consolidates all the resistances.
Fördertechnik - Griemert/Römisch [6]		1RZ 2RZ 3RZ		
Dubbel – Taschenbuch für den Maschinenbau [12]		1RZ 2RZ 3RZ 1RT 2RT		
Fördertechnik Band 2 – Zillich [13]	1RZ 2RZ 3RZ 1RT 2RT 3S	1RZ 2RZ 3RZ 1RT 2RT 3S		Introduces a resistance formula for overhead conveyors. Determination is based on the sum of empirical coefficients. A safety factor of 6-12 should be considered for this type of calculation.
Förderanlagen - Spiwakowski [14]	1RZ 2RZ 3RZ 1RT 2RT 3S	1RZ 2RZ 3RZ 1RT 2RT 3S		
Sortier- und Verteilsysteme – Jodin/Ten Hompel [5]		3T 3RZ 1RT 2RT		
Stahlgelenkketten und Kettentriebe – Rachner [15]			1T 1RZ 3S 4S	
Ketten-Getriebe – Pietsch[16]				No analytical calculations - tables and diagrams for empirical determination.
Konstruktionselemente des Maschinenbaus 2 – Sauer [17]			1T 3S	Chain design using charts, diagrams, and coefficients.
Handbuch Kettentechnik – IWIS [18]			1T 3T 2RZ 3RZ 3S	Combination of analytical calculations and empirically determined diagrams.
Die Drehschwingung des Zweirad-Kettentriebes bei innerer Erregung – Rachner [19]			1RZ 3S	Detailed examination of oscillation in chains.
Schwingungen mechanischer Antriebssysteme – Dresig/Fidlin [20]			1RZ 3S	

Inertial Forces

In all mentioned cases, centrifugal forces in the chains are neglected, with centrifugal forces in the load carriers only considered by source [9]. Inertial forces due to infeed and outfeed are calculated using energy conservation approaches but are also mostly neglected. Processes such as starting under full load are considered with high safety margins and the introduction of correction factors, leading to grossly over-dimensioned drives [8]. Emergency stop scenarios are not mentioned in the literature and are not reflected in the calculations.

Friction in Traction Element and Load Carrying Device

The calculation of frictional resistances is performed with varying levels of detail. Sources [8–10] provide a detailed breakdown and derivation of frictional resistances. Standard references like sources [5–7, 11–14], on the other hand, use empirically determined total resistance coefficients that encompass all common friction phenomena.

Dynamics – Real Operating Conditions

Weaknesses in the state of the art are highlighted by the consideration of dynamic processes and loads due to real-world operations. Many sources do not address these at all or describe them only using correction coefficients, such as [9] and [10]. The only oscillation phenomenon described in all sources is the polygon effect. How its effects behave on the overall system or the superposition of oscillation with other excitations such as oscillating load carriers, chain tensioners, or switches is not mentioned.

The influence of real operating behavior is only considered in [8], where the effect of the skewed position of the carriers is accounted for, leading to an eightfold increase in resistance force. Considering that in a pouch sorter system, where thousands of carriers are in circulation, each applying a periodically fluctuating force on the conveyor chain, it is negligent not to include such influences. Besides the sparse treatment of dynamic loads, constraint forces due to tolerance deviations are also not considered.

Conclusion from the Literature Review

The literature review has revealed several gaps. Inertial forces are consistently neglected in the literature due to their minimal influence on the magnitude of force amplitude. However, this only applies to the impact on force magnitude and not to the periodic excitation of the system. Even forces with small amplitudes but the "right" frequency can have significant effects when they match the resonance of a component.

In more recent literature sources, detailed calculations of entire systems are deemed too complex and time-consuming, thus being replaced by approximate solutions with correction factors and high safety factors (up to 6-12 according to [14]). This indicates an acknowledgment of the high inaccuracy of existing calculations, which is accepted.

The consideration of dynamic influences from real operations and their effects represents the most significant weakness in the literature analysis. This is not only due to the lack of consideration but also because these influences cannot be adequately depicted through quasi-static analysis.

Knowledge transfer from other fields is not effective in this context. While existing calculations can certainly be described in more detail, particularly regarding chains as general machine elements, a substantial amount of literature addresses chain calculations. However, no improvements can be made concerning all dynamic phenomena by combining these calculations, as they are hardly transferable to the pouch sorter system.

2.3. Metrological Approaches for Determining Chain Force

In the field of conveyor technology, there are metrological approaches for determining the chain force. The rationale behind this is that the exact determination of present loads through theoretical considerations and idealized assumptions is always limited. The quality of the analytical and numerical solutions depends on suitable description methods, accurate modeling, and the precise knowledge of the parameters used. Frequently, there is a reliance on information from manufacturers regarding the properties and characteristics of components, which are only valid within certain tolerance ranges. [21]

Opportunities for the use of measurements arise for validating analytically calculated chain forces or to determine parameters for the calculations. Moreover, measurements prove to be useful for continuous monitoring of operating systems. Overloads in the chain can be detected early, triggering warning mechanisms. Additionally, increases in friction or wear of components due to operating life can be monitored to track the aging of the system. [22]

In the field of conveyor technology, there are two main methods for measuring chain force: indirect measurement via the drive torque and direct measurement at the chain link.

Indirect Measurement

The torque can be indirectly determined either by measuring the mechanical drive torque, the rotational speed or the electrical power consumption of the drive. By converting these measurements, the resulting chain force before the drive sprocket can be calculated. [21]

Measuring the drive current requires high sampling rates in the measurement chain. Additionally, the influence of the gearbox and converter efficiency must be considered, as they depend heavily on the current load and significantly affect the measurement [23]. Mechanical torque measurement can also present several challenges. Accurate measurement often requires precise alignment and calibration of the torque sensors, which can be difficult to achieve in practice. Furthermore, mechanical sensors can be sensitive to environmental factors, which may introduce noise and reduce the accuracy of the measurements. [24]

An overall critical limitation of the indirect force measurement method lies in its inability to resolve the spatial distribution of the resistance experienced by the conveyor. This limitation arises from measuring only the total resistance at the drive location. Generally, the highest chain force is located just before the drive entry. However, due to unfavorable loading or the superposition of oscillations, the highest chain force can deviate from this position, which is not detectable in the drive torque measurement [22].

Examples of the use of indirect measurements are shown by [4, 21–23].

Direct Measurement

In contrast to indirect measurement, the direct method involves measuring the force directly on the chain itself. This approach offers the significant advantage of accurately allocating resistances along the conveyor route to specific locations.

Challenges include the limited size of the measurement technology, which must be accommodated within the confined spaces along the entire conveyor route without causing collisions or significantly altering the system. Additionally, the measurement technology must be mechanically and electronically protected against external influences, corresponding to the installed deflection points, drive stations, and switches. The continuous supply of energy to measurement technology also presents a challenge. Furthermore, data transfer must be ensured, either through the storage of data for later analysis or through real-time transmission via Wi-Fi. [25]

The implementation of direct chain force measurement is demonstrated in [25].

Conclusion of the Metrological Approaches

The primary issue with both measurement methods lies in accurately assigning loads to their corresponding phenomena. Indirect methods lack the capability to pinpoint the exact location of resistance. Similarly, direct measurement methods provide only limited insights into the root cause of the resistance. For instance, if the oscillation of the load carriers results in an increased force, this will be detected in the chain measurement. However, it is not possible to determine whether this increase in force is due to a misalignment of the carrier or the oscillation of the pouch.

In addition to the specific challenges of each method, there are general problems and challenges that apply universally. Measurements can only be conducted on existing systems, which restricts the possibility of pre-analysis for new systems. The installation and calibration of the measurement technology are labor-intensive and require specialized knowledge. The quality of the results is contingent on the measurement technology and the accompanying procedures.

Moreover, the costs associated with the measurement technology and the execution of measurements are high, which can impact economic feasibility. Tests under maximum load conditions (short-term overload) or extreme operating conditions (emergency stop) can also damage the systems and pose risks to personnel.

2.4. Numerical Solution/Simulation for Determining Chain Force

Another approach for determining chain force is numerical simulation. According to [3], the definition of simulation in VDI 3633 [26], is described as a method for replicating a system with its dynamic processes in an experimental model to gain insights of the behavior of complex systems. Simulation is employed, as per VDI 2209 [27], when a real system is not available, the experiment on the real system takes too long, is too expensive or too dangerous, or the time constants of the real system are too large. It is used for designing, verifying, and optimizing mechanical-physical structures in various phases of product development. An application in the field of logistics engineering can be found in [3].

Numerical simulations can be represented at different levels of complexity. Fundamental decisions such as the purpose of modeling, the degree of abstraction, and the required as well as available model information are crucial. Depending on these choices, systems can be modeled with varying degrees of detail. The high number of bodies, contact points, and coupling elements result in systems of equations that are not manageable through analytical solutions. It is important to emphasize that both analytical solution approaches (Chapter 2.2) and numerical simulations (Chapter 2.4) are based on the same fundamental principles. Classical mechanics, particularly the equations of motion derived from Newton's laws, are used to describe the dynamics of these mechanical systems. So the key to physical-simulative modeling lies in the ability to solve simulation models with numerous differential-algebraic equations (DAEs). [4]

Another core aspect of numerical simulation is the use of recursive solution methods. This is – according to Section 2.2, crucial for the exact calculation, as the chain force results from the summation of individual resistances, which themselves depend on the current load. This mutual[4] influence of loads can thus be represented. This allows for the depiction of highly dynamic systems and the determination of their loads and influences on the chain force. With appropriate detail in the modeling, all force increases can be assigned to their respective phenomena. Numerical simulation also provides an advantage in critical operating scenarios that could endanger systems or personnel in real tests. Once a simulation model is created, it can also be used for variant modeling with minimal effort.

Since the use of numerical simulations in the field of conveyor systems is still limited, these efforts often start from scratch. Fundamental decisions such as the purpose of modeling, the degree of abstraction, and the required model information must be made. It is essential to note that every modeling decision simplifies the real system behavior accordingly. These assumptions always lead to an approximation of the real system behavior. The quality of the results is significantly dependent on the simplifications made in the modeling process. In addition to the required expertise in the modeling process, extensive technical knowledge is also necessary to evaluate, interpret, and validate the simulation results through experiments on the real system. [3]

The use of numerical simulation in the field of conveyor technology and material handling is demonstrated by [28–35]. [4] specifically addresses the special case of pouch sorter systems.

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[4] If a reaction force is incorrectly calculated, this erroneous starting value serves as the basis for error propagation. For instance, if the chain force is increased due to oscillation and this increase is not accounted for, it has far-reaching impacts on subsequent calculations. When the increased chain force due to oscillation is ignored, the actual higher chain force is not factored into the calculations. This, in turn, affects the friction forces acting on the chain. Higher chain forces lead to increased friction forces, which means the initial value of the chain force must be further increased. This cycle continues, requiring the calculation to be restarted with the new, higher initial chain force.

3. Solution Approach for Numerical Simulation

The examination of the three analysis methods previously discussed has highlighted the current strengths but also weaknesses in the determination of chain forces. The methodology outlined in the following section offers a solution to make the description of such systems through numerical simulation more manageable. This approach aims to address the weaknesses of current analysis methods. The strengths of this methodology lie in the recursive solutions provided by numerical methods and the consideration of system dynamics and their effects. Additionally, the numerical models offer high information content and all the benefits associated with simulation studies involving various parameters and geometries.

3.1. Methodology

The proposed solution is inspired by approaches from the automotive industry. In this sector, numerical simulations have become standard practice in recent years. The automotive industry benefits from a variety of already pre-built model libraries, since this technology has been used in this sector for so long, and modeling approaches used for simulating vehicle dynamics. [3] To accurately simulate the overall vehicle dynamics, the entire vehicle is not broken down into individual components for each simulation. Instead, modeling is performed across different domains and purposes. [36]

Analogous to these, a procedure illustrated in Figure 2 has been developed for the pouch sorter system. Steps 1-3 are detailed in [4] and are therefore omitted in this paper. The focus of the current work is set on Steps 4-6. According to the modeling purpose and the required information content of the models, the appropriate model description level is determined in Step 3. After modeling (Step 4), a harmonization approach for different domains is facilitated in Step 5. These models are then integrated in Step 6 using orchestration tools, resulting in a numerical model that describes the entire system.

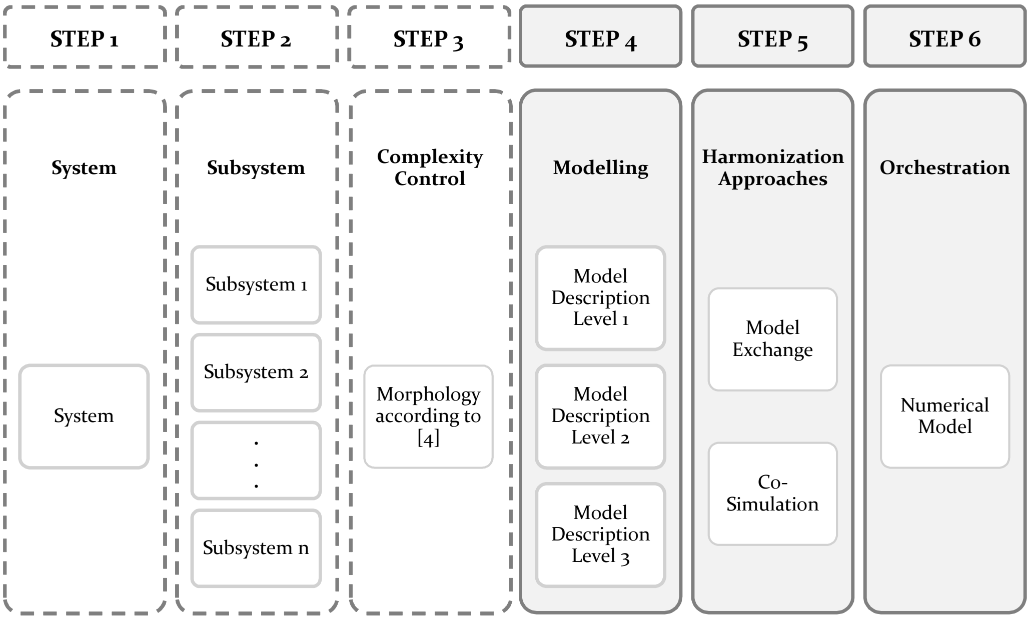
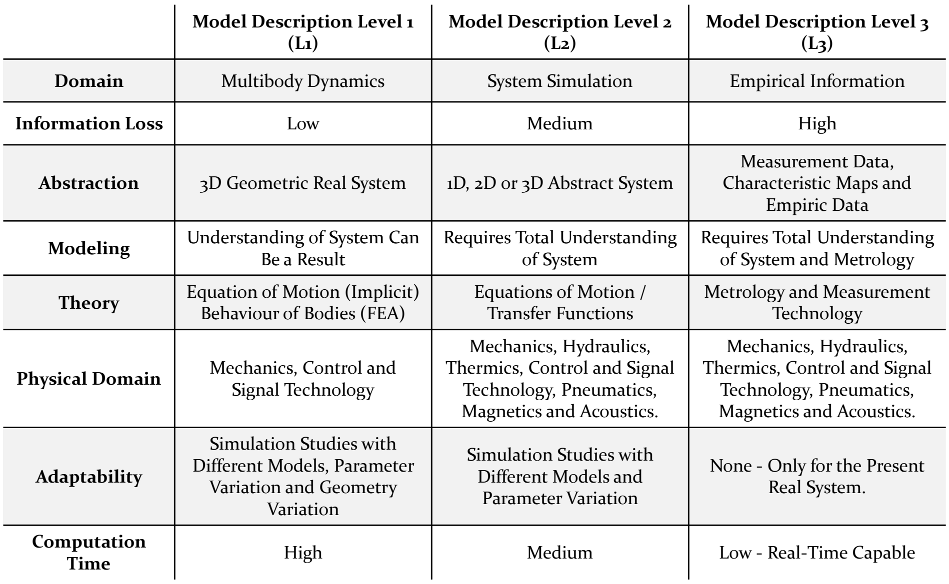


Figure 2: Method for the Use of Numerical Simulation for Pouch Sorter Systems

3.2. STEP4 - Modeling with Different Model Description Levels

The goal of modeling with different model description levels is to utilize various modeling methods depending on the purpose of the model. The system is first divided into subsystems. Each subsystem is modeled according to the required information content, ensuring that systems are only as complex as necessary. A morphology for complexity management, as shown in [4], supports the selection of the respective level. Based on information from [37], Figure 3 illustrates the contents of three model description levels. Thereby, the corresponding domains, information loss, abstraction levels, modeling methods, theoretical background, physical domains, adaptability and computation time are plotted.



	Model Description Level 1 (L1)	Model Description Level 2 (L2)	Model Description Level 3 (L3)
Domain	Multibody Dynamics	System Simulation	Empirical Information
Information Loss	Low	Medium	High
Abstraction	3D Geometric Real System	1D, 2D or 3D Abstract System	Measurement Data, Characteristic Maps and Empiric Data
Modeling	Understanding of System Can Be a Result	Requires Total Understanding of System	Requires Total Understanding of System and Metrology
Theory	Equation of Motion (Implicit) Behaviour of Bodies (FEA)	Equations of Motion / Transfer Functions	Metrology and Measurement Technology
Physical Domain	Mechanics, Control and Signal Technology	Mechanics, Hydraulics, Thermics, Control and Signal Technology, Pneumatics, Magnetics and Acoustics.	Mechanics, Hydraulics, Thermics, Control and Signal Technology, Pneumatics, Magnetics and Acoustics.
Adaptability	Simulation Studies with Different Models, Parameter Variation and Geometry Variation	Simulation Studies with Different Models and Parameter Variation	None - Only for the Present Real System.
Computation Time	High	Medium	Low - Real-Time Capable

Figure 3: Different Model Description Levels for Numerical Simulation

Level 1: Multibody Dynamics (MBD)

At this stage, comprehensive modeling with MBD is performed. The modeling is done using 3D geometries, and the motion behavior and interactions of the components are defined through kinematic and kinetic coupling elements. The 3D contact detection enables the consideration of part collisions based on their geometry. This is the lowest level of abstraction, aimed at depicting complex interactions and highly dynamic processes. Modeling with System Simulation[5] requires background knowledge of differential equation systems, which are then represented through building blocks (e.g., spring-damper systems, friction, etc.). A significant advantage of MBD is that this knowledge is only partially necessary, and models can be created without this abstraction step. The model can even provide insights into the system's behavior. This

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[5] System Simulation breaks down a complex system into individual components, each described by its physical behavior in separate simulation models. These models are combined to analyze the overall system behavior, with various physical effects calculated simultaneously. The difference between MBD and System Simulation is that MBD focuses mainly on the dynamic analysis of mechanical systems and their kinematic and kinetic properties, while System Simulation covers a broader scope by integrating different physical domains and examining the entire system's behavior, considering all interactions and effects. [38].

includes, for example, the movement behavior of components under specific load conditions. This is a distinct advantage over the other two levels. However, the downside is the high computational effort required for the simulation model. The high information content comes with an increased demand for computational capacity.

Level 2: System Simulation

System Simulation describes subsystems using abstracted models by simplifying their dynamics through the representation of signal flows and system interactions. Geometries are reduced to their masses and inertias as the kinematic behavior of these systems are calculated using point mechanics. Automatic contact detection is not provided due to the reduction of the geometries and must be represented through contact models using spring-damper systems. The remaining behavior of the components is modeled analogously to MBD as a coupling of equivalent inertias and through spring-damper systems and friction points. The advantage of this abstraction lies in the reduced computational effort. Even within this abstraction level, further subdivisions can be made. Multiple bodies can be represented as equivalent systems to further reduce computational effort. The downside of abstraction is primarily the loss of information resulting from the abstraction. Another significant point is the high level of system understanding is required to properly describe complex systems through abstracted systems.

Level 3: Empirical Information

This level describes the behaviors of subsystems using characteristic curves, maps, or empirical data. The dynamics of a system are described using characteristic curves (e.g., motor characteristic curves). The advantage here is a further reduction in computational effort, albeit with significant information loss.

3.3. STEP5 - Harmonization Approaches

After modeling the submodels at different model description levels, these submodels need to be prepared to work in an overall model. There are two ways to integrate these submodels. On the one hand, the system of equations of the submodel can be fully integrated into the system of equations of the overall model (see Model Exchange for details). Thus, eliminating the need for a separate solver. On the other hand, the submodel can also be solved by an independent solver (see Co-Simulation). The results calculated in the solver must then be synchronized with the overall model.

The term harmonization means in this context that, in principle, both approaches must provide identical results at a high level of abstraction, i.e., a clear cause-and-effect relationship between an input and an output variable needs to exist. However, this connection only must exist and it is not necessary for it to be visible in the overall model, thus enabling encapsulated, black-box style submodels.

There is a wide range of different approaches for implementation, most of which are implemented proprietarily and some of which are deeply integrated into an overall model. However, the highly specific variants that are deeply integrated into an overall model are usually only assigned to a dedicated task, making it sometimes hard to distinguish between a submodel and a part of the overall model. An example of this is

Hexagon Adams' Controls Toolkit, which enables control loops to be mapped in an multibody simulation and can be considered as a Model Exchange submodel.

Even if the proprietary tools rarely provide detailed insights into the exact harmonization of deeply integrated approaches, some of them can clearly be identified as Co-Simulations due to the mere fact of seeing two simulation tools carrying out their calculations side by side and thus sporting their own solver. Exemplary implementations of these approaches are Hexagon Adams' ASCI Interface for the Co-Simulations of MBS and Finite Element Analysis (FEA) simulations as well as MBS and Discrete Element Method (DEM) simulations, or RecurDyn's Particleworks Interface for the Co-Simulation of MBS and DEM simulations.

Apart from the proprietary approaches, open standards have been developed as well in recent years. In this case special exchange formats are required to facilitate the combination of the submodels. Among these, the most used exchange format is the Functional Mock-Up Unit (FMU). As the most used exchange format is the FMU, the exact differentiation between Model Exchange and Co-Simulation will be shown using the descriptions of this open standard.

FMUs are components used within the Functional Mock-Up Interface (FMI) standard for the exchange and Co-Simulation of dynamic models. They enable the integration of various numerical simulation models developed in different tools or environments, allowing for complex multi-domain simulations where different aspects of a system are modeled using the most suitable tools. [39]

Numerical simulation models are described by differential, algebraic and discrete equations, incorporating time-, state-, and step-events. To solve these complex systems, appropriate solvers are employed. The choice of solver is critical as it directly impacts the accuracy and efficiency of the simulation. Different solvers are optimized for various types of equations and computational loads. The correct FMI type, whether Co-Simulation (CS) or Model Exchange (ME), must be defined to align with the specific requirements of the chosen solver and the system being modeled. Two most common types of FMI are Model Exchange and Co-Simulation. [39]

Model Exchange (ME):

Model Exchange provides an Ordinary Differential Equation (ODE) to an external solver (as can see in Figure 4) of an importer or overall model. Models are described by differential, algebraic, and discrete equations with time-, state-, and step-events. The importer, typically an ODE/DAE solver (Differential-Algebraic Equation), is responsible for time progression, setting states, and handling events. [39]

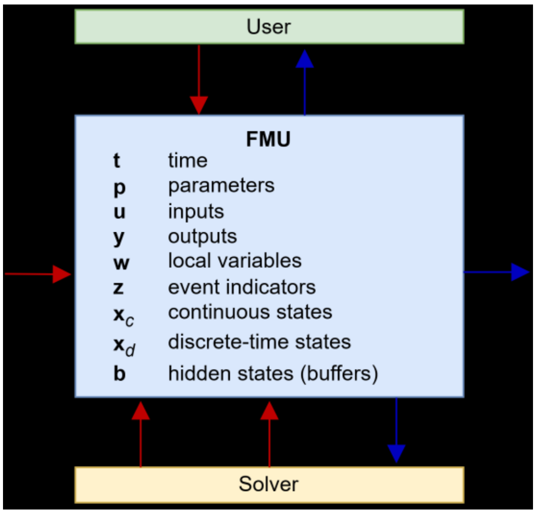

Figure 4: Functional diagram - Model Exchange [39]

Co-Simulation (CS):

In contrast, the FMI for Co-Simulation interface is specifically designed for coupling simulation tools and subsystem models. This approach allows different simulation tools to work together, each handling specific parts of the overall system. The Co-Simulation interface facilitates the integration of these tools, ensuring they can exchange data and synchronize their simulations effectively. [39]

Subsystem models, along with their respective solvers, are exported as executable code from the modeling environment, as shown in Figure 5. By encapsulating the solver with the model, Co-Simulation allows for the decoupled simulation of models, meaning each subsystem can be simulated independently, using its own solver, without needing to be re-integrated into a single monolithic solver. [39]

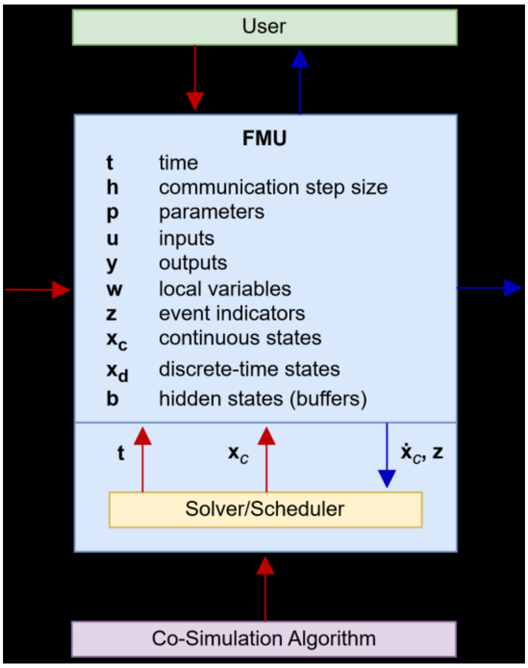

Figure 5: Functional diagram – Co-Simulation [39]

As a second variant of Co-Simulation, an FMU can also be used purely as a synchronization interface. In this case, both simulations involved are executed in separate programs and the FMU is only used for synchronization.

3.4. STEP6 - Integration with Orchestration Tool

According to the chosen model exchange format, a higher-level structure is required to enable the combination of individual submodels. In the case of harmonizing the overall model using a Co-Simulation approach, during the simulation, intermediate results such as variables and status information are exchanged between these tools. They are synchronized at discrete predefined communication points, while running independently between these communication points. [40] The orchestrator is responsible for aligning the exchange variables described in the interfaces and coordinating the different time schemes of the various simulators, ranging from event-discrete and time-discrete to continuous simulation [41]. In the case of using a Model Exchange approach, the role of the orchestration tool is carried out by the simulation environment of the overall model.

Tools for System Simulation, such as Simulink by MathWorks, DYMOLA by Dassault Systèmes, or SimulationX by ESI ITI, as well as specialized software designed specifically for model exchange, such as Maestro and PyFMI by Modelon and DACCOSIM by EDF, are used to couple individual FMUs into complete systems.

Figure 6 illustrates an example of how a black-box model can be constructed for the drive chain system. The system is divided into the subsystems “Drive Chain” and “Load Carrying Device”, with the latter further subdivided into the “Carrier” and “Pouch” subsystems. This black-box structure provides a clear example of how the interaction between various subsystems is established.

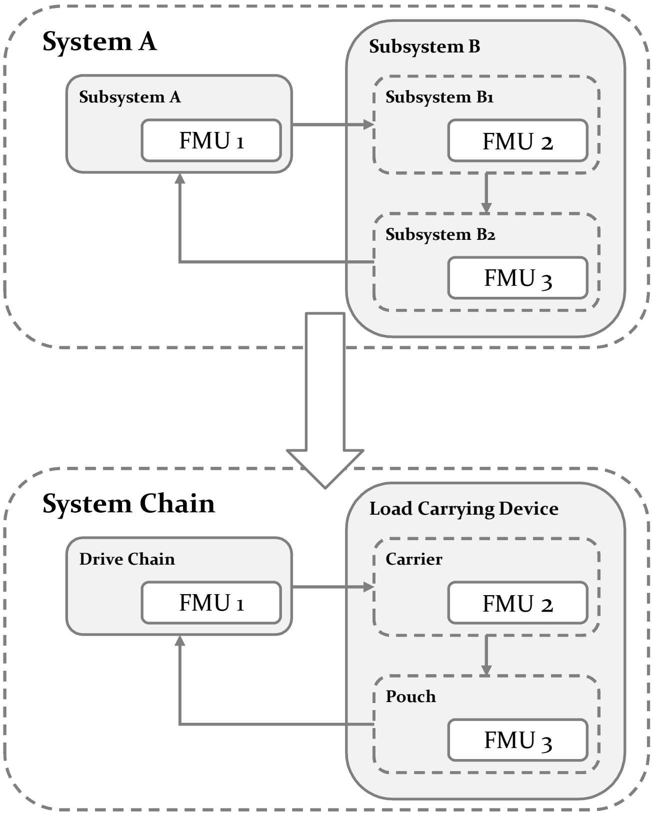

Figure 6: Example for a Black-Box Model of the Chain System

3.5. Application Examples of the Methodology

For the previously mentioned method, exemplary modeling approaches for the pouch sorter system are now presented. In the first example, the influence of oscillating pouches on the chain force is determined. The second example focuses on investigating the reaction force on the tooth of the sprocket.

Problem – Influence of Swinging Pouches on the Chain Force

When dividing the system into subsystems, the subsystems identified are the carrier + pouch, chain + guide rail, and drive station. For modeling the subsystems, the carrier + pouch system employs the lowest level of abstraction, a MBD System. This system can describe the entire dynamics of the subsystem. The chain + guide rail system is represented using a System Simulation approach. Here, the chain is modeled using point masses coupled by spring-damper systems, friction elements and external forces. Depending on the level of detail, different discretization can be applied. This means that either each individual chain link is represented as a mass with respective coupling elements and resistances, or a defined number of links is combined into a substitute model. The resistances of the guide rails are modeled with friction elements. The reaction forces acting on the chain from the carriers are depicted as unidirectional forces, originating from the FMU of the carrier + pouch system. The characteristics of the drive station are modeled using a motor characteristic curve, which is integrated as an input variable in the FMU of the chain + guide rail system.

A graphical representation of this process can be found in Figure 7. In the first two steps, the division into the aforementioned submodels is shown. The required model description level is determined by the morphology for complexity management. In the fourth step, symbolic images of the respective domains are used for illustration. The exchange of models is carried out via Co-Simulation, where each model uses its own solver. Orchestration is performed in this case within the simulation environment of SimulationX software by ESI ITI.

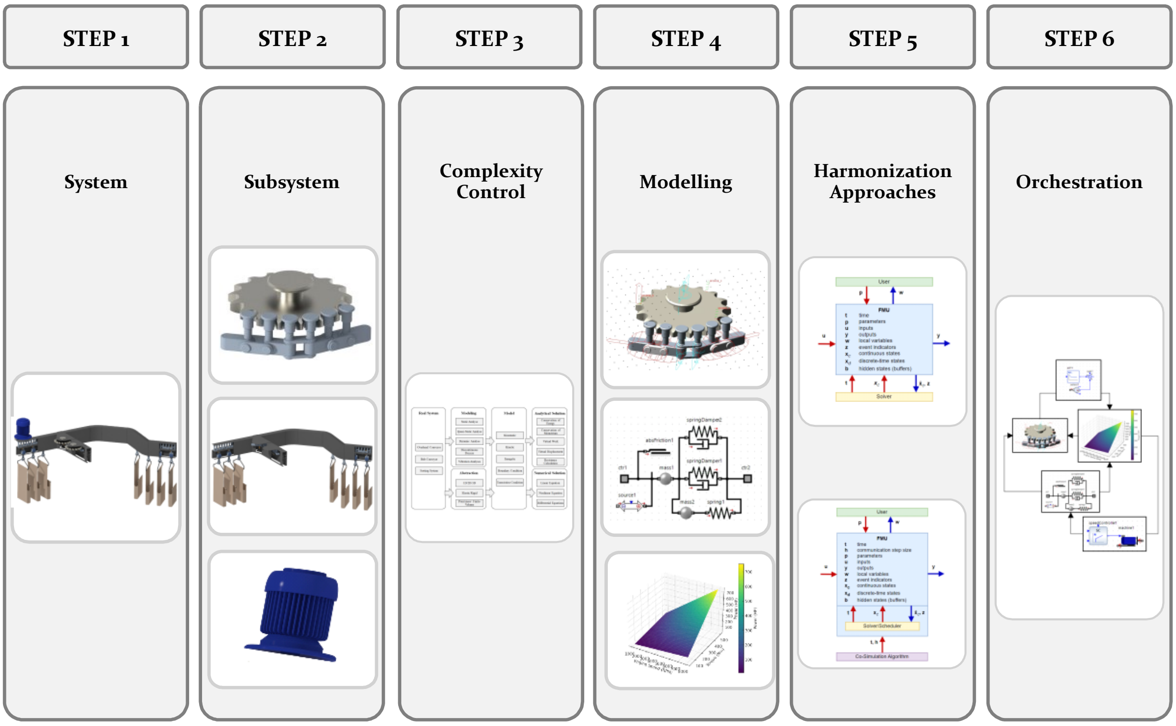

Figure 7: Modeling Approaches - Influence of Oscillating Pouches on the Chain Force

Calculation Problem – Reaction Force on the Sprocket

In this division into subsystems, the identified subsystems are Chain + Guide Rail + Carrier + Pouch, Chain + Sprocket, and Drive Station. For modeling the subsystems, the Chain + Sprocket system employs the lowest level of abstraction through a MBD System. However, only a small number of freely oscillating chain links are modeled rather than the entire chain. This approach allows the determination of the influence of the freely oscillating chain on the sprocket tooth engagement. The sprocket and the chain links around the engagement area are represented using 3D geometry.

The remaining system, Chain + Guide Rail + Carrier + Pouch, is represented using System Simulation. Here, the chain is modeled using equivalent masses coupled by spring-damper systems. The resistances of the guide rails are again modeled as friction points, and carriers and pouches are represented by equivalent masses. The interface between the two submodels is the chain force, which functions as the input and output variable for the FMUs. Thus, the chain force of the system is transferred as an external force to the MBD model. The behavior of the drive torque is represented as a characteristic map and is passed to the Chain + Sprocket FMU via an FMU.

As in the previous example, Figure 8 provides an illustrative depiction of this process.

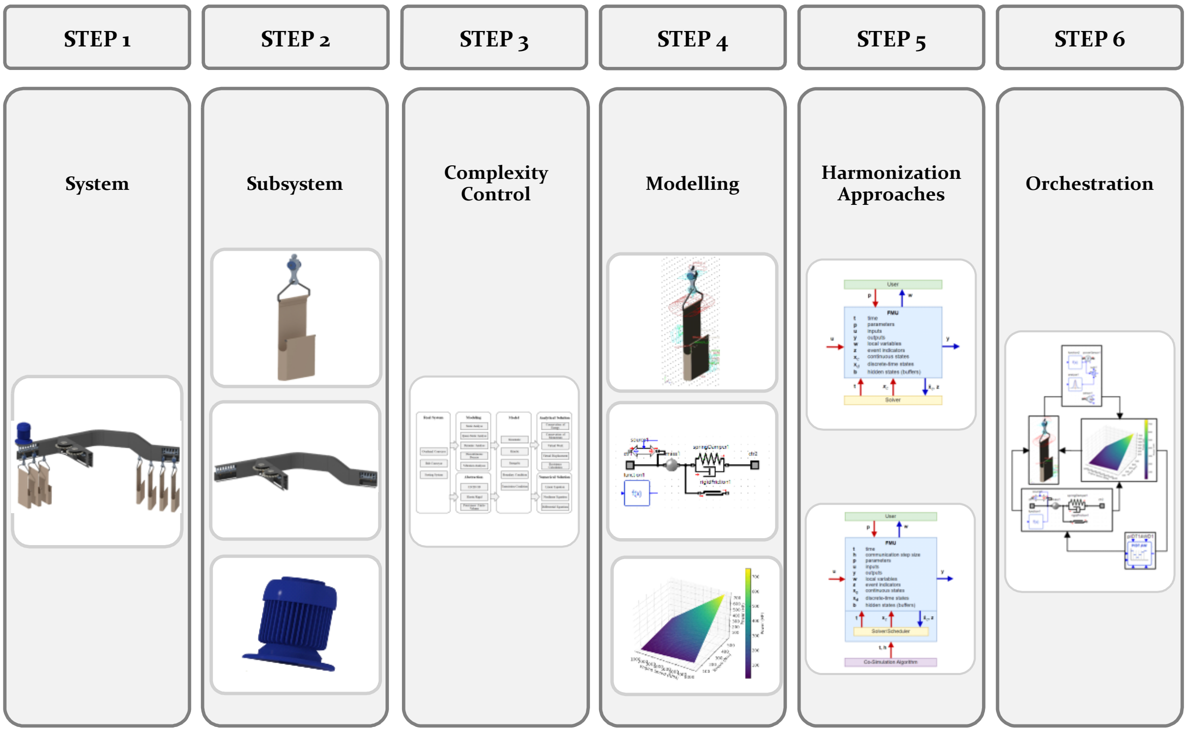

Figure 8: Modeling Approaches - Reaction Force on the Sprocket

4. Conclusion and Outlook

This section provides a final discussion and summary of the proposed methodology, along with an outlook for future research.

The comparative evaluation of analytical, metrological, and numerical simulation methods has revealed significant insights into their respective advantages and disadvantages, as outlined in Section 2. The methodology proposed in this work demonstrates potential solutions to bridge the gaps identified in current practices by leveraging the strengths of numerical simulations. By incorporating dynamic processes and recursive solutions, the approach offers a more comprehensive understanding of system behavior. Furthermore, the ability to conduct extensive simulation studies with varying parameters and geometries provides valuable insights for system design and optimization.

The focus of this work is on the segmentation of the system and its modeling at various model description levels. This segmentation is crucial for making such approaches manageable. It can lead to significant progress in system understanding, reducing the need for over-dimensioned systems, and thereby enhancing sustainability and energy efficiency.

While there are notable advantages, there are also challenges to consider. The use of multiple simulation domains brings significant complexities and requires substantial expertise in these areas. Licensing costs for the various resources used are also a concern. Moreover, the success of the methodology is highly dependent on the decisions made during model formation. Poor decisions in the initial steps of subsystem formation and modeling can significantly affect the success and quality of the methodology. In addition to the aforementioned challenges in selecting submodels, the fundamental success also lies in the accurate modeling and, most importantly, the parameterization of the individual submodels. As with any model, it is crucial that the chosen models and parameters are appropriately determined for the specific application.

This work aims to highlight the gaps in existing analysis methods and address them through the presented approach. Applications in this area, as demonstrated in [4], have already shown initial successes and have proved to be effective. The described approaches can be extended to the area of drive chains, making them applicable in other fields as well. The described project will be further pursued in the context of a Ph.D. thesis by the author Kröpfl.

In conclusion, the methodologies outlined in this study represent a significant advancement in the analysis and design of pouch sorter systems. By addressing the limitations of current practices and incorporating dynamic simulations, we can achieve more accurate, efficient, and reliable system designs. The ongoing refinement and application of these techniques will continue to drive advancements in intralogistics and conveyor technology.

Contributor Roles

Conceptualization: P.K, A.O-P., C.L.; Methodology: P.K., A.O-P., C.L.; Formal analysis: P.K.; Investigation: P.K., A.O-P., M.S.; Writing – Original; Draft: P.K., A.O-P.; Writing – Review & Editing[6]: P.K., A.O-P., C.L.; Visualization: P.K., M.S.; Supervision: A.O-P., C.L.; Project administration: A.O-P., C.L..

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