General Structure of a Digital Control Twin Model for Production and Material Flow

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Abstract. This paper is about the general structure of a Digital Control Twin (DCT) Model to regulate production, transportation, and handling of material flow items. At first the basic elements of the general structure and the functionality is described by special terms to achieve a common understanding about the general concept and for a easier discussion of future research. Based on this general approach the elements of a specific DCT-Model for production and material flow processes is explained in more detail. This specific DCT-Model could be a platform for a future ERP-System, especially of material requirement planning as the core module. Then some restrictions and limitations of this specific DCT-Model are treated in short. At the end a short resume and conclusion for further research is made.

Keywords: Digital Control Twin Model, Production and Material Flow, Material Flow Item, Repository, Digital Trigger, Digital Shadow

1 Introduction

The emergence of Industry 4.0 is creating new challenges, but also new opportunities for operational and business processes, and especially for production and logistics. New concepts, methods, tools and IT systems are required to control production and the flow of materials inside and outside the factories of manufacturers and suppliers. In order to take advantage of the large amount of process data collected, the high speed of data processing and data transmission, the real and virtual worlds must be connected in new ways. This connection should be as close as possible in order to use the process data directly or to control the process as closely as possible. Classic concepts such as ERP/MRP-II-Systems, which were designed in the 1980s, are no longer up to date. The new approach of the Digital Control Twin Model can master the challenges and take advantage of the opportunities of Industry 4.0.

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2 The Concept of the Digital Control Twin Model

2.1 The idea of the Digital Twin Concept Model

The Digitization is a phenomenon that accompanies industrial enterprises since decades. But with emerge of ‘Industry 4.0’ digitization reaches a new level with a wide range of new technologies and intelligent tools and IT-Systems. One of the most important trends for the next decade is the “Digital Twin”. During the last years the issue of brochures, presentations, and papers about “Digitalization” and “Digital Twins” are increasing steadily.
“The Digital Twin model was first introduced in 2002 as a concept for Product Lifecycle Management (PLM) without giving the model a name (Grieves, 2002). The model was soon named, but the name has changed over time. It was originally named the Mirrored Spaces Model (MSM) (Grieves, 2005), but later changed to the Information Mirroring Model (Grieves, 2006). The model was finally referred to as the Digital Twin (Grieves, 2011), a name that John Vickers of NASA had coined for the model. While the name has changed over time, the concept and model has remained the same…” [Grieves, 2019, p. 177]. “*It contains three main parts: a) physical products in ‘Real Space’ b) virtual or digital products in ‘Virtual Space’ and c) the connections of data and information that ties the virtual and real products together*” [Grieves, 2014, p.1] (Fig.1). Each single physical product is a replication of the virtual product (describe in IT-System of CAD, CAE, CAM etc.), and the manufactured products can be compared with the virtual product and deviations can be exploited for execution of the actual manufacturing process, also for maintenance of the technical equipment and for design of the next product generation.

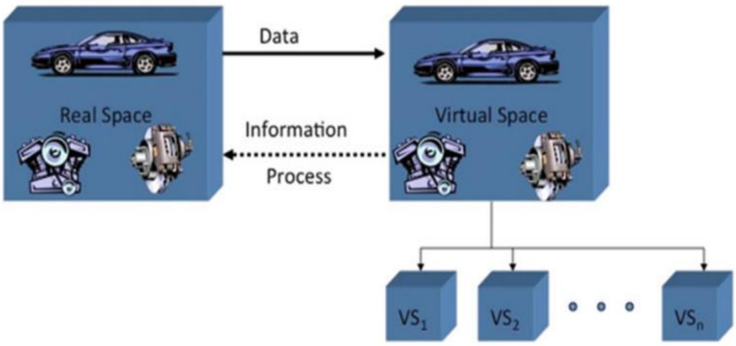

Figure 1. The Digital Twin Concept Model of Grieves/Vickers [Grievs,2019]

Engineering companies like [SIEMENS] or General Electric [GE] are developing Digital Twins which focus on technical aspects of products, production, and material flow e. g. to control machinery and assembly line execution, or control of material handling equipment or transportation means. The best-known purpose predictive maintenance of machinery and assets and execution management of assets. One example is the control of distributed energy resources and electrical networks e. g. for forecasting and maintenance of electrical grids etc. Another example is the Digital Twin for monitoring the complete railway-network which covers the railway infrastructure itself and all technical devices like crossings, signals but not the transportation carrier and transportation equipment like trains, wagons etc. (Fig. 2).

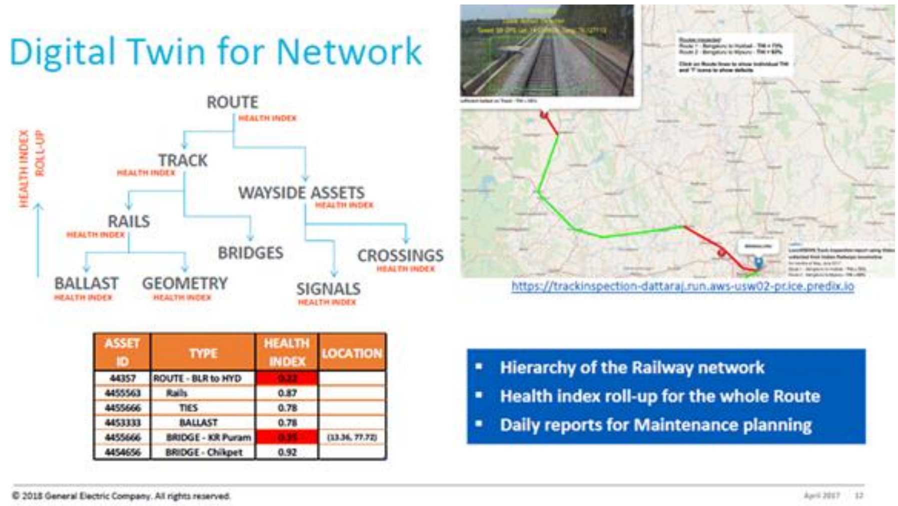

Figure 2. The Digital Twin a technical Network [GE-1]

In production and logistics, we can distinguish between a technical-oriented DCT and process-oriented DCT-Model; the process-oriented DCT-Model focus on the transportation process, which uses the technical network which is the precondition for the process and defines environment and constraints of the usage. In the following we concentrate on the process-oriented DCT-Model. Most Digital Twin Models in production and logistics are technical and engineering oriented. Nowadays there exists a lack in research for value-added chains in general and especially in the development of concepts especially for order-oriented control production and logistics. [Zadek, Herlyn, 2020]. One reason for this is probably that the concept of Grieves cannot simply used for production and material flow processes. Because production and material flow depend on different individual customer orders, the time and the process environment, which are changing permanently and are not a replication of the virtual world.

2.2 Digital Control Twin Model for Production and Material flow in general

The DT-Model of Grieves/Vickers must be transferred into the environment of production and material flow and for this the concept must specify the bidirectional relation of the real world and virtual world of material flow. For this we formalized the concept by introduction of some standardized contents and terms: (1) Reality is now the real world of production and material flow with the focus on the right material items, time, location and quantity. The reality is mapped as virtual world in the Repository

(2), where all relevant data are digitally stored. The basic data items for production and material flow are the material flow items (‘#’), material flow nodes (‘o’) and material flow edges (‘--'), which built a network wherein all material flow items can and must move. (2) Repository means the virtual world and covers all digital data that are required to map the real world for the purpose of regulation. (3) Regulation is the software resp. the tools, methods, and algorithm to control production and material flow items. (4) Digital Triggers are output resp. result of the regulation to influence the reality in a certain direction. (5) Digital Shadows are the relevant process data of the reality, which are required to compare the real world with the virtual world, to detect target-actual deviations and to renewal the regulation (Fig. 3).

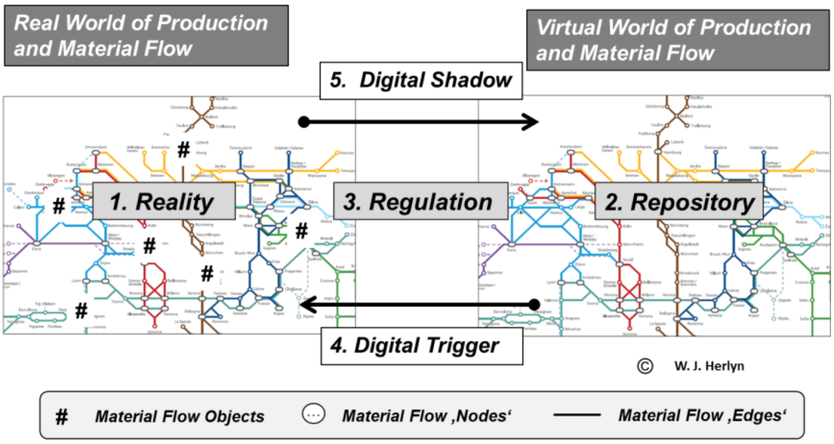

Figure 3. General Concept of a Digital Control Twin Model for Production and Material Flow

In production and logistics, we can distinguish between technical-oriented DCT and process-oriented DCT. An engineering oriented DCT-Model for a railway-network focusses on the infrastructure, technical devices like crossings and signals. A process-oriented DCT-Model focus on the transportation process, the using of the technical network which is of course the physical fundament. In the following we concentrate on the process-oriented DCT-Model and for this it is decisive what type of material flow items will be observed and what is the purpose of the regulation. Depending on this decision the kind of mapping production and material flow is chosen and the also cycle-times of regulation for issuing Digital Triggers and for gathering Digital Shadows is to decide. So, there will be different ‘types’ of DCT-Models to regulate production and material flow and for each type we have to specify a specific structure and functionality of the DCT-Model. Depending on the concrete material flow item and regulation purposes the methods and algorithm must be chosen. In some cases, a planning tool is appropriate in other cases optimization or simulation is a better tool. Also, the kind type of Digital Shadows and Digital Triggers can be variate. Consequently, the DCT-Model and its five defined elements must be clearly defined for different purposes of production and material flow control.

3 The first examples of the Digital Control Twins

3.1 First examples of Digital Control Twin Concept in Logistics

The first appearances of a digital control twin did not yet have any particular theoretical background and were not referred to as digital twins. Rather, it was about the practical use of new techniques and devices for the registration of objects in the running process. It was a simple reaction to the emerging new technologies such as GPS, RFID and communication via the Internet, which enabled logistics companies in particular to monitor and track the status and location of goods in transit. Now there are several applications of DCT in the field of logistics, mainly focused on technical aspects to control the flow of materials. This concerns not only pure transportation, but also the handling, storage and distribution of goods [DHL].

3.2 Track and Trace

One of the first application of a DCT in logistics was the well-known concept of 'track and trace'. This concept was introduced by Logistic Companies like UPS or [DHL] to control the shipping of goods and inform the customer that the ordered good is on transport, where it is now and when it will hand-over.

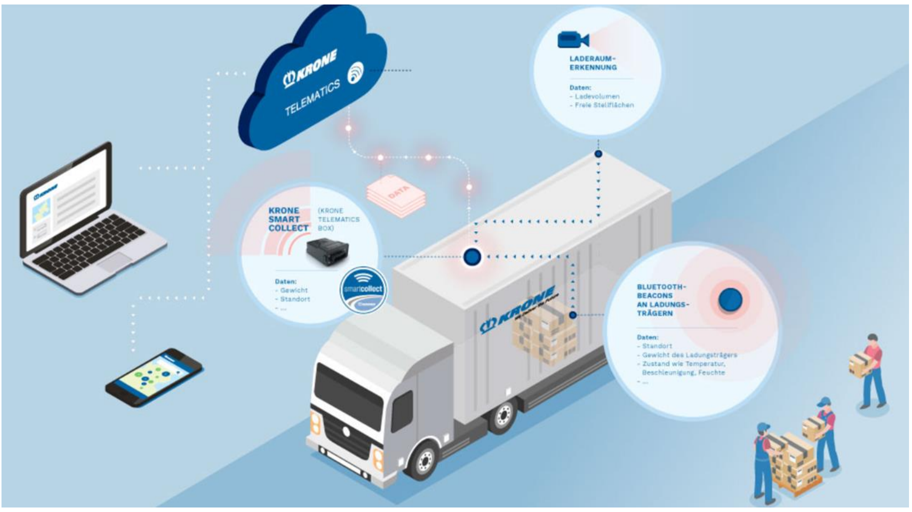

Figure 4. Example of Track and Trace [Krone]

Meanwhile track and trace is standard not only in distribution processes but also in supplying chains and inhouse transportation. Especially the idea of a 'Digital Supply Chain' is addressed by a lot of research institutions [IPA, IOSB, DFKI], consulting firms [Gartner, Deloitte], logistic companies [DHL] and leading software-companies

[SAP, IBM] are developing and integrating Track and Trace into their ERP-Suites which are used by OEM’s and suppliers [Krone] (Fig.4).

3.3 Production Control Center in the automotive industry

The automotive OEM have installed Production Control Center (PCC) in their car factories since years, to monitor the production and flow of vehicles, starting at the welding shop of car bodies over the car body painting shops and car warehouses up to the final assembly lines, finishing shops and final quality check center (Fig. 5).

Figure 5. Production Control Center in a Car Factory [Jungmann]

The focus is on monitoring manufacturing and the internal flow of vehicles and the availability of all assets and technical equipment and the IT-System focus on deviation of technical equipment an issue ‘Hints’ or Alerts’ Hints and ‘Alerts’ if technical problems are detected or if the volume targets of production are not achieved. [VW, AUDI]. But the IT-System cannot react directly because the control of the production is enclosed in other IT-Systems planning, control and execution like MES or MRP. The stuff of the PCC has to inform the experts and the plant management, who had to decide what to do and - after decision making – to ‘adjust’ the different ERP-Modules. The focus of PCC is on technical process control but not on order processes. This is a big lack in process control which has to be filled out by the new approach based on the DCT-Model. And in addition, the existing PCC doesn’t cover the processes of material items. A passenger car is configurated individually by a customer and consists of up to 10.000 components and these material items must be available at the right time, place, and quantity to manufacture all cars in the factory. The PCC must be converted into a Logistic Control Cockpit for all kinds of material items and all sections in the factory and for the entire supply chain. For the future PPC-Concept it is necessary to use immediately actual process data by RFID, QR-Code or Cyber-Physical-Objects of products and of all components to react in-time and to harmonize all processes in only one IT-Systems [Zadek, Herlyn, 2020].

4 The Digital Control Twin for Production and Material Flow

4.1 The specific Digital Control Twin for Production and Material Flow

The main task of logistic for manufactures is to ensure that the right material is available in the right amount at the right time at the right place or production. This task is planned and controlled by orders and schedules for material flow objects, whereby the starting point are the customer orders for final products. For this a specific DCT-Model has to be designed (Fig.6).

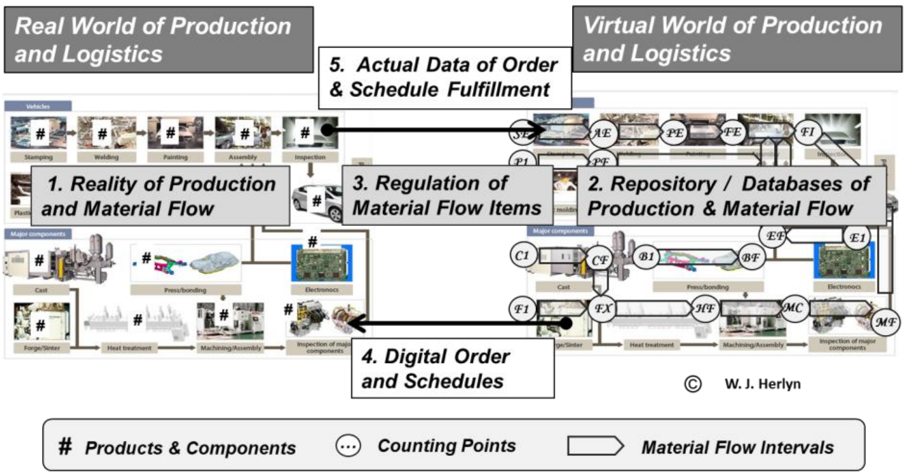

Figure 6. Digital Control Twin Model for Production and Material Flow

1. Reality: Reality stands for the actual processes of production and material flow that must be permanently planned, controlled, and monitored. Reality means all activities of manufacturing, transportation, storing, handling of material flow items. This are normally final products, and all kinds of dependent components like modules, assembly groups, single parts and raw material. But it also includes the complete infrastructure for manufacturing transportation and storing of goods and all transportation and handling means and carrier. Because production and material flow is a continuously ongoing process it must be structured into intervals resp. material flow sections with discrete points where the process can be influenced by orders, and the results can be measured by order fulfilment.

2. Repository: The Repository consists of all databases which relate to each other. The term database does not mean exactly one specific database, it's more a synonym for a certain content of information and can be stored in different ways by a couple of connected 'physical' databases. Repository is the digital representation (virtual world) of the reality and includes Transaction-Data, Master-Data and Control-Data. Transaction-Data means all kinds of order-oriented data like customer order or Master Production Schedule (MPS). Master-Data means all order-independent data and covers the structure of production and material flow, product structure stored as Bill-of-Materials and Transportation and Handing including packaging, sorting and handling. Control-Data means all kinds of disposition parameters to control the process and all required activities of production and material flow. The Repository covers not only material flow items like final products and its component, but also means for transportation and handling like container, bins, trucks, tugger-trains, shelves etc. The repository covers all data to plan, schedule, control, monitor and balance actual processes by issuing orders and schedules for all involved process partners and equipment for the right material items, right time or sequence and right places. In the DCT-System all applications share a common Repository instead of classical ERP-Systems which are connected by interfaces and data-exchange processes.

The backbone of the Repository is production and material flow (PMF) structure which is connected with the product structure and Transportation Structure. The material flow of discrete products is not arbitrary but linear oriented and follows the structure of the production process itself and the delivery network of components is depending on this. "Today most material flow systems are networks because the process is partly organized in series or parallel" [Arnold, Furmans, 2019]. This network can be mapped by an ideal Boolean Interval Chain whereby the intervals are bounded by Counting Points (CP) which have a strictly ordered sequence [Herlyn, 2014]. These CPs are used on the one side for regulation of the process by Digital Triggers (placed orders and schedules) for material items in the corresponding interval. And on the other side for Digital Shadows (fulfilment of orders and schedules) which are actual process data to measure the results. The accuracy and the speed of regulation response is extremely important and determines the type and granularity of the PMF-Structure.

3. Regulation: Regulation covers all kinds of algorithm and methods for planning, scheduling, monitoring, and balancing of production and material flow. This includes especially the generating of different schedules for manufacturing, transporting, and warehousing and calculation of orders for all involved shops and equipment. The main task of regulation is to ensure that the right material items available in the right quantity, at the right time and the right place. The exact order quantities of final products and components must be determined for the entire network. The main regulation method bases on the principal of Closed-Loop-Control; whereby placed orders and schedules are the target values and fulfilled orders, and Schedules are the actual values. Deviations of target and actual values are evaluated and balanced by the regulation software using the predefined execution rules.

Figure 7. Order-Entry-Point: RFID-tag attached at the car body [AUDI]

The Counting Point where the vehicle order is connected to the real physical product is called the 'Order-Entry-Point' (OEP) also called as 'Order Decoupling Point' [Wiendahl, 1997, Herlyn, 2012], This CP is especially crucial not only to control each single car but also all cars together therefore it is taken for regulation of the complete factory. In automotive production the OEP is laying in the manufacturing section of car chassis welding where an ID-Plate or RFID-Chip is attached at the car chassis e. g. the side beam or cross beam of a vehicle chassis or the end of the chassis (Fig.7) [AUDI].

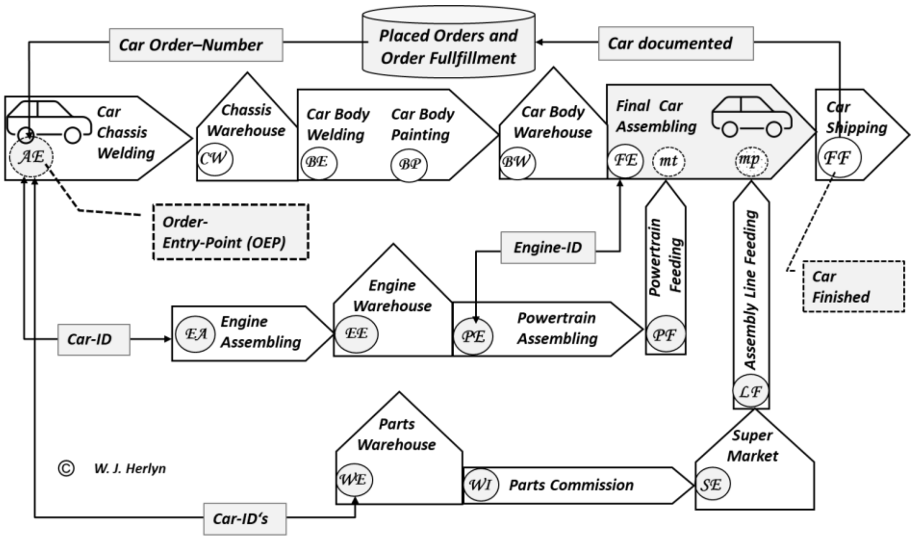

Figure 8. Regulation of Products and Material Items in a Car Factory (exemplary)

In a car factory we can take the CP 'AE' as Order-Entry-Point and thereafter we can relate all required material items to a unique Car-ID in advance, e. g. the car engine or any material items which is called the pearl chain concept (Fig. 8). For control of feeding the car manufacturing process with required components we must use a couple of Car-ID's because material items are transported, stored or handled in lot-sizes. If a component is already manufactured and stored, then it can be commissioned directly to a certain Car-ID. If a component is not available already an order for manufacturing or assembling etc. must be issued, e. g. by a Jit- or Jis-Call. We can apply this procedure for other (appropriate) CPs, so we get a data grid to control all dependent components for all shops and warehouses inside and outside the factory for the cars in the factory, which is called the pearl-chain concept. For control and order release we must know the lead-time (LT) which the main parameter is to control final products and components over all shops, warehouses etc. LT is the real elapsed process time between two next-following CPs in the interval chain. Because of the ideality of PMF-Structure we can add up the LT of the next-following intervals, so the complete LT of an object is the sum of all passed intervals resp. CPs. For LT-calculation neither the kind of operation (production, transportation, storing or handling) nor the 'physical length' of an interval is relevant. Once and only the real elapsed time between two CP's is the decisive factor. This is also valid for all areas in expanded supply or distribution chains. An in the future especially for Smart Factories with autonomous production control, where Cyber-Physical-Objects can search the next manufacturing, transportation, or handling station by their own [Zadek, Herlyn, 2021].

4. Digital Trigger: Digital Triggers are all kind of orders and schedules, that are placed and transmitted to a specific device, a shop, a department, business partner or human. Digital Triggers control the real process of manufacturing, transportation, storing and handling of material items. At the end Digital Triggers must be executed by humans or devices and build, also the input for an engineering oriented Digital Twin the process. It is not always possible or make sense to transmit the orders immediately to the devices, places, or partners, where they are needed. Orders and schedules must be issued in different ways and at different times and are controlled by the specific cycle-time of the specific process taken in account the technical and organizational conditions. Therefor a specific regulation tool controls the issuing of orders and schedules to avoid problems for technical processes and shops on shopfloor level. and departments. If orders are issued to early, then the process can overact and if orders are issued to late than the process can be delayed, and process partners can react too late and resp. or in an inappropriate manner.

5. Digital Shadow: Digital Shadows are actual acquired data of real processes at a certain time and locations (counting point) and the state and quantity of an identified material items. The Digital Shadow is not the whole items itself but more a snapshot, and it's very important that Digital Triggers and Digital Shadows refers to identical items and locations at a specified time or timeslot. Not every acquired data is automatically a Digital Shadow. Only those process data that are captured at a defined

Counting Points and time are used as a Digital Shadow. The data can be acquired in different ways, by different devices and techniques and it can be entered also by hand or scanned by Bar-Code or QR-Code, gathered by an active or passive RFID-Chip, or transferred by a Cyber-Physical-Objects which can itself store, process, and transmit data. For the DCT it does not matter which type of data acquisition, technique or device is used, all that matters is that the acquired process data is available at the time when it is needed for the specific regulation purposes. In an order-oriented DCT-System Digital Shadows are the fulfilled orders and schedules that comes from different steps in a process and are often generated extremely fast and in a huge amount. For some application it makes no sense to use the process data immediately because the usage depends on specific regulation task and response time in the concrete process. Therefore, a process cycle-time is needed to pass the process data to the referring application in an appropriate cycle time and manner. Process data are acquired normally on the shop-floor level, the lowest level of scheduling and order calculation. Knowing the relation between the processes, the PMF-Structure, and the application we can control the process by a defined cycle-time for each interval which is crucial for the update and data processing. It makes no sense to calculate every second new order data for all applications. The same also applies to the processing of the collected data. At the lowest PMF-Level we need the latest actual process data, but we should process the data not real-time but only in the corresponding process cycle time. The reason is that the lead-time of material flow in an interval and the response time of the process must be balanced to react on process data with new orders and schedules. If the defined cycle-time of processing is too slow than the reaction by Digital Triggers comes too late. If the cycle-time is too fast than the reaction by Digital Triggers comes to early, and the process gets nervous and is over-controlled. So, cycle-times must be defined for all Intervals in the PMF-Structure depending on the corresponding regulation task.

4.2 Some Restrictions of the order-oriented Digital Control Twin Model

The DCT-Model for production and material flow depends on the underlaying network and therefore on the suitable method of mapping the PMF-Structure. In the case of control of a complete factory the suitable network must be defined for all final products and components, which are manufactured therein, so the DCT-Model can run only for completely defined customer orders of final products which are stored in a Master Production Schedule. This could be sometimes a problem, if there are a lot of spare-parts or other ‘exotic’ parts. The regulation of the described DCT-Model covers only a short-run horizon, where customer and dealer orders are available in a MPS because the regulation bases on an existent Order-Entry-Point for final products in the factory. The impact range of the regulation is limited if the lead-time of the manufacturing process for the final product is shorter than the lead-time of the required components. The regulation of components with a longer lead-time must be controlled by earlier available information or forecasting- For regulation of a mid-run and long-run horizon for strategic tasks like product and sales planning or forecasting of material demand other different DCT-Models must be developed and cannot incorporated into the short-run DCT-Model. For such purposes a specific DCT-Model with special tools for forecasting and aggregated planning are required, and other types of mapping network and other methods, algorithm and procedures are needed. Because of the huge data-grid of Counting Points in a big factory for complex products a high-performance computing concept (e. g. a Qbit-Computer or High-Performance Computer) is needed.

5 Conclusion and short Outlook

The DCT-Model is a new approach to control production and material flow using the capabilities of Industry 4.0, especially to exploit the acquired process data of material flow items that are available thru new technologies like RFID, QR-Code etc. The development of such DCT is still in its early stage but the existing DCT in factories can be introduced step by step to all material items in a factory. The existing production control center and applications can be enhanced to an entire DCT-System, for this the regulation of products and material flow items must be transferred into the overall control software of the complete factory. The process and order oriented DCT is complementary to the engineering oriented Digital Twin Concept, both can and must be combined. This will lead to a paradigm shift in business informatics of production and logistics. One of the results is that planning, control, execution and monitoring of production and material flow is now in only one IT-System and no more separated in different IT-Systems and ERP-Modules. The DCT-System can react immediately on process deviations and disturbances by using the potentials of permanent available process data. Overall, the DCT-Concept can not only speed up the control of production and material flow processes in factories of complex products it is also an adjustable and resilient concept with higher performance, better control, and more flexibility than existing ERP-Systems and IT-Concepts [Herlyn, 2021].

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