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Mastering the Supply Chain by a Concept of a Digital Control-Twin

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Purpose: The purpose is to design a new concept for control of the Supply-Chain for the era of industry 4.0 exploiting the huge amount of actual data of material flow objects which are available thru new identification technologies, localization and communication systems and to use appropriate tools for evaluation and analyzing actual data.
Methodology: The approach uses the idea of a Digital-Twin Concept for logistics that bases of three pillars: 1) 'reality': actual status of material flow objects 2) 'repository': digital mapping of material flow objects 3) 'regulation' of material flow. The real and virtual material flow objects are permanently compared, deviations are evaluated and harmonized by using the principle of closed-loop-control.
Originality: The concept is a very new approach to master material flow for final products and required components. For this a 'Big- Picture' of a Digital Control Twin (DCT) System is designed, which is a necessary complement to the engineering oriented Digital-Twin-Concept to run a smart factory.
Findings: The paper shows how the idea of a Digital Twin Concept for engineered products can be transferred into the world of logistics and especially for supply chains. The Digital Control Twin controls, monitors and balances material flow objects according to quantity, location and time and can help to predict and solve problems in advance.

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1 Introduction

Digitization is a phenomenon that has accompanied industrial companies for decades, but with the emergence of 'Industry 4.0' digitization reaches a new level through a variety of new technologies, intelligent software tools and cloud-based communication. One of the most important trends is called "Digital Twin" which focusses on the beginning mainly on engineered objects. Meanwhile many international logistics companies are integrating a 'digital supply chain' into their portfolios. New identification technologies, localization and communication systems are creating not only new challenges but also new opportunities for companies in productions and logistics management. The huge amount of permanent available data requires a new concept to master the supply chain, which gets more importance because of increasing product variants and globalization of production and supply chain networks. The existing methods to control supply chains base on ERP-/MRP-concepts which have some weak points: 1. The using 'water-fall model' has no feedback and recursion to a preceding or higher level 2. Order instruction are calculated by the 'gross-net-method' which is hardly useful for Digital Twins 3. Existing ERP-/MRP-Systems use a fixed schema of algorithms that is hardly adjustable for different logistic and operational task and application levels (Stadler 2015, Wiendahl, 2011).

1.1 The Emergence of the Digital Twin Concept

The "Digital Twin Concept" (DTC) was elaborated and introduced by Michael Grieves and John Vickers. Their concept "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). The permanent communication between the real and virtual world is the crucial point because in the past the DT was more a 'simple' digital mapping of an object. Their concept referred to engineered objects, which are accordingly described by engineering data as Computer Aided Design (CAD) and Computer Aided Manufacturing (CAM), you can find a literature overview by (Kritzinger, 2018, Johns 2020). But an engineering-oriented DTC is used for design, manufacturing and maintenance of physical objects and cannot directly used for logistics objects and order-oriented processes.

1.2 The Digital Twin Concept for Logistics and Supply Chain

The Digital Twin Concept is hardly treated in standard textbooks of logistics and supply chain or operations management (e.g. Schuh, 2013, Bauernhansl, 2014, Kilger, 2015, Schönsleben, 2016, Klug, 2018, Stevenson, 2018, Heizer, 2020). Scientific papers offer different approaches like data-model-based and driven-concepts (Ivanov 2019, 2020, Chankov, 2016), simulation or stochastic based algorithms (e.g. Timm, 2015, Lorig, 2015, Rodicz, 2017, Uhlemann, 2017, Kunath, 2018). Several papers, whitepapers and recommendations of institutes focus on Cyber-Physical-Objects and autonomous process control as a core part of a smart factory and smart logistics (e.g. Plattform Industrie 4.0, WiGeP, Fraunhofer IML, Luściński, 2018, Farahani, 2020). International logistic companies (e.g. DHL 2018) and leading software houses (e.g. SAP 2019) are developing concepts of DT for better logistic performance and lower cost in supply chains. Their concepts are focused on technical and handling aspects and monitoring of flow objects mainly, they are not order-oriented, and an overall planning and control of MF are not really included.

In this paper we focus on a deterministic and rule-based regulation between the real and virtual logistic world which is a crucial part of a Digital Twin Concept of Grieves/Vickers. For industry 4.0 a holistic concept is needed where real and virtual logistic processes are controlled and harmonized in one IT-System (Zadek, 2020). For this we transfer the idea of Grieves/Vickers into the world of logistics for planning and monitoring of material flow objects (MFO) in a production and material flow (PMF) network. For this we give some terms a name slightly different to make it more understandable for logistic applications. We call the three pillars in short: Reality, Repository and Regulation. We call data that flow from real to virtual world ‘Digital Shadow’ and information that flow from virtual to real world ‘Digital Trigger' (s. fig. 1). This is the basic idea and fundament to design a DCT-Concept for logistic purposes that means to control, monitor, and regulate MFOs in a dynamic logistic and time-driven environment.

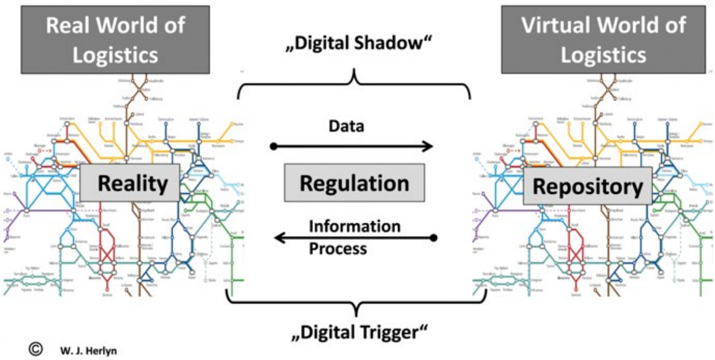


Figure 1: Three Pillars of the Digital Control Twin Concept for Logistics

To make sure: There is a general difference between an engineering and logistic oriented DTC. The target values of physical objects like CAD/CAM-Data are fixed in time and are replicated by instances but in logistics target values like order quantities are changing and must be balanced over time. Therefor a logistic-oriented DTC must treat objects and data with other methods than an engineering-oriented DTC because of the different characteristic of the observed objects, processes, and tasks. The logistic oriented DTC must ensure that the right MFO is available at the right place, at the right time and in the right quantity over a certain time-period.

2 Big Picture for a Digital Control Twin System

For logistic purposes we design a Digital Control Twin (DCT) System which is illustrated by a Big-Picture. The main three pillars are explained in short:
1. Reality: By "Reality" we mean a certain cutout of interested MF-Sections and MF-Objects whose flow should be controlled. If we look at a manufacturer this includes the production and transportation of the end-products and all necessary components (modules, assemblies, individual parts, etc.). A part of reality is all kinds of transporting means like trucks, trains etc. and loading means like bins, container, racks etc. and real routes or railways are a part of logistic reality too.
2. Repository: Under "Repository" digital mapping of MF-Reality in corresponding databases is understood. The "Repository" stores are all kinds of master-data (like Network- and Product-Structure) as well as further control data, which serve for the description of the material flow and for the assignment of all MFOs. Master data are order-independent and includes work calendars, control data for material dispatching etc. On the one hand we have order-dependent 'transaction data', which includes e.g. sales orders and production schedules as well as order for required components.
3. Regulation: "Regulation" means all kinds of planning, monitoring and balancing MF of MFOs including determination of schedules and order calculation. The main task of regulation is to ensure that the right MFO must be available at the right time, in the right quantity and at the right place. For this purpose, the exact order quantities of products and components must be determined for the entire PMF-Network. Target values or placed orders are transmitted to the operation units and called 'digital trigger'. Actual registered values represent the fulfillment of placed orders and are

called 'digital shadows'. The type of data acquisition and recording can be carried out using various tools and identification systems like barcode, RFID etc. Both digital trigger and digital shadows represent the real and virtual logistic world only at a certain moment and are balanced by a certain algorithm of the DCT-System. The DCT-Controller reacts to any situation by means of defined rules and control instructions. All results are stored in a Data-Gravity-Center and can be analyzed by Data-Analytic-Tools and used for predictive 'maintenance' and optimization of logistic procedures or data (s. fig. 2).

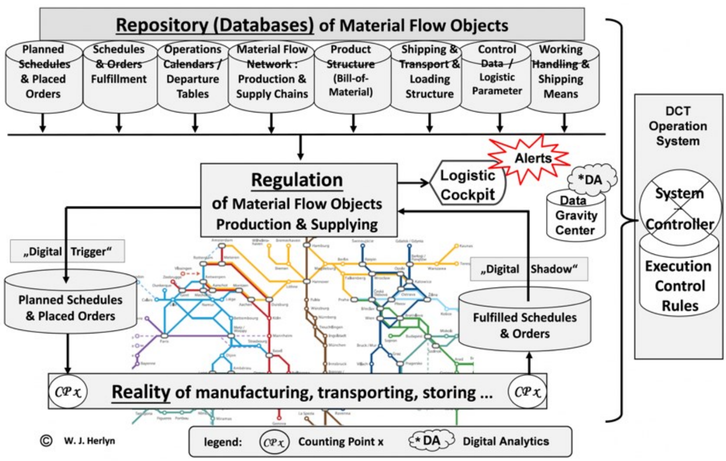


Figure 2: Big Picture of a 'Digital Control Twin' System

2.1 Reality of Material Flow Objects and Data Acquisition

Logistic 'Reality' covers all kinds of manufacturing, transporting, storing, sorting, distributing etc. of all components, e.g. raw material, single parts, assembly groups, modules etc., that are required to produce final products. Reality covers all kinds of logistic means like bins, boxes or trucks, trains or ships which are necessary for fulfill orders and schedules. All logistic activities are performed in a MF-network wherein all kinds of material items have to move like transportation routes, factory grounds, shops and halls, railways, harbors or distribution center, warehouses, stores or buffers.

Digital Shadow: Real material flow items leave a ‘Digital Shadow’ which is registered by special tools, devices, and IT-Technologies. Digital Shadows are all kinds of data which comes directly from the real MFOs. The Digital Shadow should cover at a minimum the quantity, current state, and location of a single or a couple of correct identified items. The data can be acquired in different ways and by different techniques supporting by different technical equipment and features. Data Acquisition (DA) can be entered into an IT-System by hand or scanned from a Bar-Code or a QR-Code or acquired by an active or passive RFID-Chip. In the future bigger components become more and mor 'Cyber-Physical Object’ which can store, process and share data and is identified by an IP-Address. For a DCT-System it does not matter which kind of data acquisition techniques is used, its only that data are available for the DCT-System when they are needed, this is the crucial criteria for the appropriate technique of data acquisition.

DCT-System must be always ‘on-air’ to process the real und virtual data parallel and permanently. This does not mean that the DCT-System must know the values and status of every MFO at every moment and every place.

The calculation of the target values and the comparison with the actual data is carried out for each MFS in a certain defined cycle time (CT), which is aligned to the LT of the real process of the respective MFS. A Digital Shadow is like a snapshot which is taken from time to time and shows the reality only at that time.

The DCT-System itself is 'real-time' oriented and can have a linkage to all other processing IT-concepts depending on the concrete tasks. A characteristic of DCT-System is the capability to use and combine different concepts of data processing and operating systems. This allows us to use data from older IT-Systems that are ‘batch-oriented’, more modern IT-System that are ‘online oriented’ and latest IT-Systems that are ‘cloud-oriented’. The actual data can be processed from different sources, at different times and different locations by different IT-modules which can be a part of another IT-System. The execution of the DCT-System is carried out by a System-Controller, which works by means of control instructions and rules. The control instructions, rules and cycle-times for regulation are stored in a database that is maintained by experts from specific departments.

2.2 Repository - Databases for Mapping the Logistic World

Repository maps all data that are required to plan, control and monitor MFOs which represent the virtual logistic world and stores them in different specific databases:

1. Material-Flow-Network or PMF-Structure 2. Product-Structure (PS) normally known as 'Bill-of-Material' (BoM) 3. Shipping-Structure that includes transport, loading and packaging data 4. Operational or Working Calendars, including departure- and arrival-dates for shipping and starting- and

ending-dates for manufacturing 5. Control Data also known as disposition parameters 6. Capacity Data for describing technical assets, equipment and working means 7. Planned schedules and places orders for all MFOs 8. Fulfilled schedules and orders for all MFOs.

In the following we will explain only the Material Flow Network and Product Structure and Lead-time (LT) and Lot-Size (LS) as the main logistic parameter of Control Data.

2.3 Digital Mapping of Production and Material Flow Structure

In the center of the 'Repository' stands the mapping of the production and material flow (PMF). There are various methods for mapping production and material flow such as flow charts, tables, matrices or graphics. Normally the material items flow from a source only in one direction to a sink, it has built up a linear flow structure, but "today most material flow systems are networks because the process is partly organized in series or parallel" (Arnold D., Furmans K., 2019). The material flow of discrete products is not arbitrary but linear oriented and follows the structure of the production process itself and the supplying network is depending on this. This linear type of network can be observed in industries such as the automotive industry (Herlyn, 2012).

For mapping we use the mathematical theory of an ideal Boolean interval lattice. We assume that the material flow of discrete products can be represented by a linear ordered chain of Boolean intervals which are closed open defined by a left and right boundary and should meet the requirements of an ideal Boolean interval lattice. There are no jumps or overlaps between the next following intervals, no interval in the chain is missing or lies outside the entire interval whereby each interval is defined as closed-open. The beginning is defined by an 'Entry Point' (EP) which lays inside the interval and the end is defined by another EP which lays outside the interval and must be the beginning of the next-following interval. The complete algebraic definition of intervals and subintervals is omitted here for reasons of space. Detailed information about Boolean Interval Algebras can be found in (Koppelberg, 1998, Herlyn, 2012, 2017).

2.4 Ideal Boolean Intervals and Real Material-Flow-Sections

The described PMF-Structure is at first only a logical structure but not a physical representation of the real logistic world. For this it is necessary to link this logical structure with the physical material flow structure. Each EP of the logical MF-structure must be referenced to an existing Data Acquisition Point (DAP) and only then we get a Counting Point (CP) thereby. By this strictly ordered CPs material flow, e.g. a certain transportation, can be planned and monitored although the concrete transportation carrier can use different routings and loading means. This referencing method has many advantages because structural data is very stable and can be adapted easily to different changes and new conditions in practice. Another advantage is that several DAPs can be referenced to only one logical EP. An example: if there is less space for storing goods in a plant incoming goods are received at different 'goods-receipt-points' in logistics centers outside the plant boundaries. For the logical structure it does not matter whether the physical DAPs are located internally or externally of a plant or company.

And when a DAP has moved from one location to another, only the reference between logical CP and physical DAP is changed but the logical PMF-structure remains the same.

2.5 Mapping of Product Structure as Bills-of-Material (BoM)

PMF-Structure must be supplemented by the Product Structure (PS) in order to incorporate and identify MFOs. The PS describes all required components of a final product and is stored as a 'Bill of Material' (BoM). Product data are required to plan and calculate concrete shipping, manufacturing, stocking, or delivery orders for components. Due to the complexity and configuration of the end products the PS can be stored in different BoMs which use specific methods to map substructures. Without any reference to the PS the defined PMF structure is only a needless and empty framework, PMF and PS together built the backbone of the DCT-System. For each manufacturing interval we need a specific BOM which contains all items that are used in the concerned interval; The Complex-BOM for a is linked to the CP ''FF' (end of final assembly line) and contains all components of car variants (s. fig. 3). Depending on the type of manufacturing process and complexity of products different types of BOMs are used (Schönsleben, 2016).

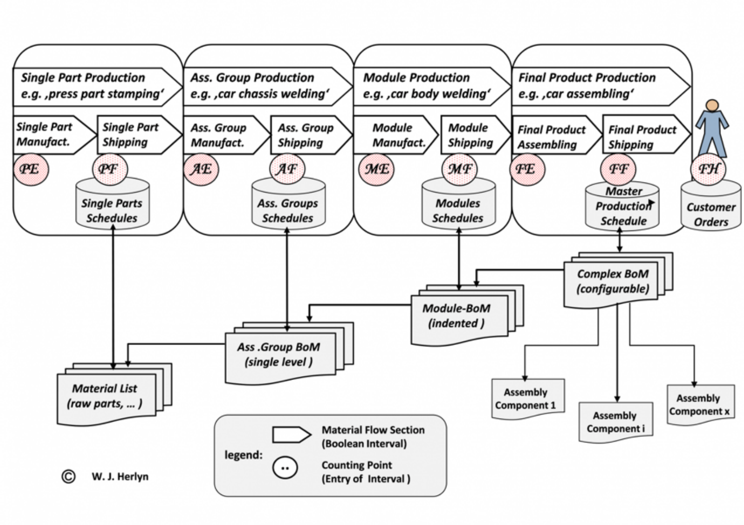


Figure 3: Reference of PMF-Structure and Different Kinds of BoM

We distinguish four typical types of BOMs that are adapted to the type of production for single parts, assembly groups, modules, and final products. Each BoM is linked to the ending CP of the corresponding manufacturing interval which is starting CP of the next-following interval. In the DCT-System there is a strong requirement that each ending CP of a manufacturing section must be referenced by one specific BOM and vice versa each specific BoM must be linked to a certain unique CP.

3 Regulation Methods for the DCT-System

Regulation for the DCT-System means generally all methods, algorithms and tools to plan, calculate, schedule and monitor the flow of MFOs. In a DCT-System we cover under regulation not only planning methods and tools but also simulation and optimization methods and tools. The DCT-System can combine these different tools and methods for planning and scheduling MFOs but here we focus only on planning methods especially for depended components of an end-product.

3.1 Digital Trigger and Material Flow Regulation

Digital Trigger: In our case Digital Triggers are nothing else then placed orders or planned schedules that are calculated by the regulation software. Placed orders and planned schedules are used as target values for process controlling by a ‘Closed-Loop-Cycle’. But there is a crucial difference if we compare ‘Digital Trigger’ of material items with an engineered product: target values of an engineered product are the data of a CAD-System and are replicated by an instance every time (Grieves, 2014). Target values of an MFO are changing in time because the regulation is a dynamic one. Target values for planned schedules and placed orders are calculated permanently referring to changing customer over time and, actual order values are also updated permanently.

In connection with the LT the reaction or response time (RT) of MFO and the cycle-time (CT) for new targets values plays an important role. On the one hand CT depends on the required LT and RT is additively influenced by factors such as batch sizes and departure times. If the CT is (far) below the RT, then the real process cannot keep up with the virtual process so the system will react too quickly which will lead to hectic and incorrect reactions. If the CT is (far) above LT then DCT-System reacts too slowly, which can lead to material shortages and provokes additional avoidable costs.

3.2 DCT-Regulation and Closed-Loop-Control

The **regulation** of MFOs by the DCT-System can be carried out by the principle of 'Closed-Loop-Control'; the 'Digital Trigger' is nothing else than a target value and the 'Digital Shadow' corresponds to the actual value in a closed loop cycle. For each CP, the target values are determined in a certain Cycle Time (CT) and compared with the actual values at this time. The values are compared and by deviations they are harmonized via the DCT-regulation algorithm. As soon as the target values for orders have been calculated they can be compared with the actual order fulfillment. The deviation between the planned target and the registered actual value is evaluated for each MFO according to defined criteria, which are stored in the database for execution and control rules of the System-Controller. If critical deviations are detected certain 'Warnings' or 'Alerts' are issued and visualized via a Logistic-Cockpit. And automatically a certain regulation tools/method is initiated by the DCT-Controller to balance target and actual values. It is obvious that the appropriate method of regulation depends on the type of process. In the following we can show this on one example only (see below).

3.3 Control-Data resp. Logistic Disposition Parameters

Control-data: This database contains all disposition parameters for planning of material flow and for calculation of schedules and orders for all

MFOs. The exact setting of the control data is an important influencing variable for planning and must be carried out very carefully for each MFS and each MFO. Here we focus on lead-time (LT) and in combination with the lot-size (LS) for transportation or manufacturing which are the most important logistic parameter for regulation.

3.4 Lead-time and Planning of Material Flow

3.4.1 Lead-time and the Role for Control of Material Flow

Lead-time, also called ‘flow time’ or 'throughput-time', is a crucial element in a DCT-System is the most important parameter for MRP-/ERP-Systems. Although LT is of central importance it is not possible to go into all aspects which can be read in (Wiendahl, 1997). Here we will concentrate on LT in a supply chain.

“The total time spent by a flow unit within process boundaries is called flow time” (Anupindi et. al, 2012). In an ideal PMF-Network LT is the elapsed process time between two next-following CPs. Every Interval resp. MFS has its own LT which is transferred to all MFOs passing through. Because of the ideality of PMF-Structure we can add the LT of all next-following intervals so the completely LT of an MFO is the sum of all passed intervals. Thus, if a single part is a component of an assembly group which itself is a component of a higher assembly etc. then the total LT of this item is the sum of all passed MFS until the completion of the final product. We use the ‘reverse’ of LT (RLT) for backward-calculation to determine the ‘right time’ for MFOs by ‘shifting’ the MFOs along the CPs of the PMF-Structure. For backward calculation neither the kind of operation (production, transportation or storing) nor the ‘physical length’ of an interval is important, once and only the real elapsed time between two CP’s is the decisive factor. Any kind of MFO is equal "rated" even if the process character or environment is different. If we are interested in the total LT of a specific MFO we add the individual LTs s of all passed PMF sections. By backward-calculation we can determine at which time the concerned MFO should pass the concerned CPs from single part fabrication over installation in an assembly group or module which is mounted into the final product. We can do the same for a complex supplying process with different material flow sections.

3.4.2 An example for using different Lead-times in a delivery process

Lead-time is one of the most important parameters for MRP-/ERP-Systems and for the DCT-System. Since the LT is an attribute of PMF-Structure we must define alternative MFS for means of transport or routes etc. to be able to differentiate the LT for MFOs. In the following example (s. fig. 4) we define for the same delivery task (upper Interval) three alternative delivery concepts (lower Intervals). The upper MFS (Int-D) is defined by a beginning CP 'D' and an ending CP 'GR' (goods receipt) and consist of three ideal embedded sub-intervals (Int-D(1), Int-D(2), Int-D(3)), each of them covers exactly the upper interval, therefore the beginning and ending CPs of them match exactly.

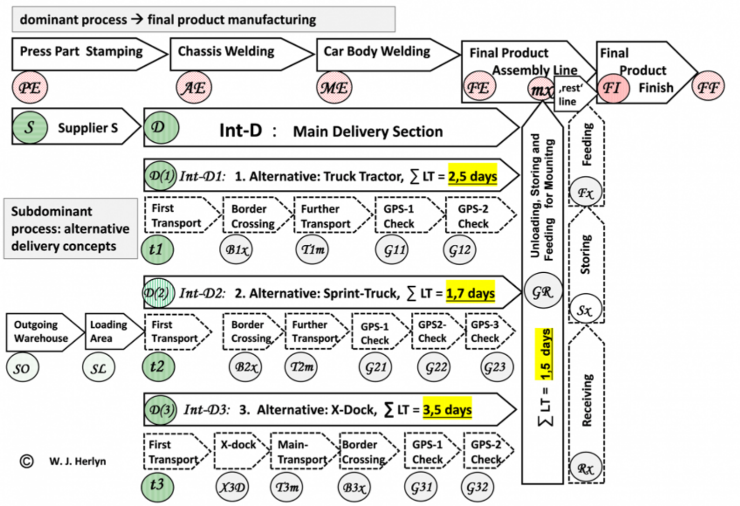


Figure 4: Definition of Alternative Delivery Concepts

Each of these sub-intervals is divided into strictly ordered next-following sub-sub-intervals whereby each represents a certain section in the supply chain and has its own a beginning and an ending CP. But each of these alternative delivery-intervals has its own specific sub-intervals and CPs for discrimination of the delivery process.

1. **Direct Shipping by truck tractor**: By this concept transportation is performed directly from goods loading at the supplier to the unloading at the OEM by a truck-tractor. For this concept, the MFS (Int-D (1)) and CPs are defined: 1. First transport: CP 't1'; 2. Border crossing: CP 'B1x' 3. further

transport: CP 'T1m' 4. GPS-Check: CP 'G11' 5. GPS-Check: CP 'G12' 6. Goods Receipt: CP 'GR'. The complete LT from CP 't1' to CP 'GR' for this concept is about 2.5 days.

2. **Direct-Shipping by sprinter trucks**: In this case the transportation (Int-D (2)) is performed by using a small truck instead of a truck-tractor. By this concept, LT is lower because of less speed-limitation or weekend-bans. By this the shipping lot-size will be lower and the frequency of delivery will be higher so the response time will be lower, and flexibility is higher to react on order changes or actual deviations so this concept can be useful in some critical situation. Although the transportation route could be the same as for truck-tractor, we need a separate MFS to differentiate LT and LS. The complete LT from CP 't2' to CP 'GR' for this concept is about 1.7 days.

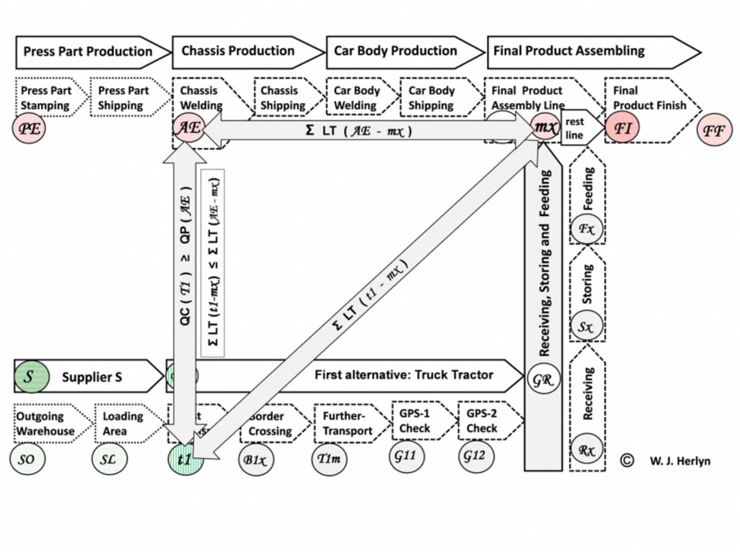
2. **Direct-Shipping by sprinter trucks**: In this case the transportation (Int-D (2)) is performed directly by using a small truck instead of truck-tractor. By this concept, LT is lower because of less speed-limitation or weekend-bans but the shipping lot-size will be lower and logistic cost are higher. The frequency of delivery will be higher so the response time (RP) will be lower, and flexibility is higher to react on order changes or actual deviations so this concept can be useful in some critical situation. The concrete transportation route could be the same as for truck-tractor, but we need a separate MFS because of different LT and LS. The complete LT from CP 't2' to CP 'GR' for this concept is about 1.7 days.

3. **Shipping using a Cross-Dock**: In this case the components are not transported (Int-D (3)) by one freight unit only, but a Cross-Dock is used for trans-loading goods, whether to put together different components in bigger container or to use bigger freight means for cheaper transportation charges. In addition, the X-dock can be used also for safety stocks and for

optimization of shipping and space in freight-carrier (e.g. fully loaded container) which will expand LT in shipping. In this case the overall LT from CP 't3' to CP 'GR' is about 3.5 days.
Hint: Here we ignore the cost aspect and other relevant factors which must be taken in account normally.

3.4.3 The Magic Triangle to Control a Complex Supply Chain

The PMF-Structure itself is only a neutral framework, for control of MFOs we need additional information about the relationship of MFOs inside this framework. Therefor we define a dominant process that represents the production of the final products and several sub-dominant MFS for depended MFOs. This allows us to control and monitor material flow of all depended components at certain CPs (s. fig. 5). Our focus is on the right time, right place, and right quantity of all right MFOs. For this we use the concept of Cumulative Quantities (CQC) to get a completely overview about the planed status and target values of all MFOs in the network (Herlyn, 2014, 2017). We will explain this only for a certain case by an example of car manufacturing. First, we built the Cumulative Curve of the final products (e.g. cars) at the very last CP 'FF' (Final Products Finished) by adding up the single orders which are stored in the MPS along an equidistant timeline. Thereafter we calculate the curves for all preceding CPs of car manufacturing and components by shifting the quantities of final products along the defined CPs using the corresponding LT for the MFS. By this method we can calculate curves for all required components. Each component must have a common CP with the final product, e. g. a takt of assembly line, where the component is mounted into the product which we call therefor a "Mounting



Point" (MP). By this procedure, all Curves relate to the final product curve and can connect with each other. After calculation of curves for all CPs step by step, we get a data grid of quantities for all components and their corresponding PMF-Structure. This data grid can be used for different logistic purposes e.g. to predict if actual shipped quantities of a component is sufficient for a secure supplying of final assembly line. Example: we compare the actual QP of cars at CP 'AE' with QC of components at CP 't1' whereby CP 'AE' can be the Order-Entry-Point, CP 't1' is the loading point of components and CP 'mx' is the 'takt' in the final assembly line of cars.

For comparing CQs of final products and components at a certain time and for certain Counting Points and we formulate a condition: only those CPs

Figure 5: Magic Triangle for Control of Delivery of Depended Components

of the dominant process are chosen where the LT between two preceding CPs is ≥ than the LT of two preceding CPs of the sub-dominant process whereby both processes referring to a common CP, e.g. a certain MP 'mx' in the final assembly line:

$$QP\ (n) \ = \ \sum_{t=1}^{n} P(t)\ ; \quad t = \ 1 \dots x \dots n \qquad (1)$$

$$QC\ (n) \ = \ \sum_{t=1}^{n} C(t)\ ; \quad t = \ 1 \dots x \dots n \qquad (2)$$

$$LP\ (p) \ = \ \sum_{p=PE}^{FF} LP(p)\ ; \ \ p = PE \dots < AE \dots < mx \dots < FF \qquad (3)$$

$$LC\ (c) \ = \ \sum_{c=SO}^{FF} LC(c)\ ; \quad c = \ SO \dots < t1 \dots < mx \dots < FF \qquad (4)$$

$$\sum_{p=AE}^{mx} LP(AE : mx) >= \sum_{c=t1}^{mx} \quad LC(t1 : mx) \qquad (5)$$

The delivery process is only secure if the quantity of component at the time 'x' QC(x) and the Counting Point CP 't1' is equal or higher than the quantity of products at the time QP(x) and the Counting Point CP 'AE'.

$$QP(x)\ (AE) \ = \ QP(x + LP(AE : \ mx) \quad ; \ \ t = \ 1 \dots x \dots n \qquad (6)$$

$$QC(x)\ (t1) = \ \ QP\ (x + LC\ (t1{:}\, mx) \ \ ; \quad t = \ 1 \dots x \dots n \qquad (7)$$

$$QC(x)(t1) \ - \ QP(x)(AE) \ \ \geq \ 0 \ \ (6); \ \ t = 1 \dots \ x \dots n \qquad (8)$$

By this method we can compare actual values for a component at every CP with the target values data for final products to evaluate if a problem can occur or not. We will show this by a concrete example using the above defined delivery alternatives. The overall LT for shipping components by truck tractor is about 5 days and should cover 2400 final products at Friday but only 2340 components are actual shipped by the supplier (s. fig. 6; upper dotted line). The quantity of 2340 components will cover final product assembling only until the end of Thursday. In this case the lower limit of target

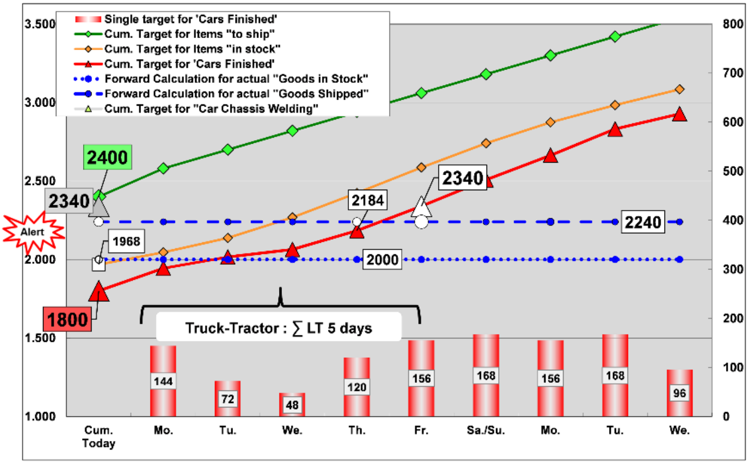


Figure 6: Standard Delivery Process by a Truck Tractor

values has been violated and DCT-Controller must change to another delivery alternative if possible.

In this case the delivery process is changed from truck tractor (alternative 1 with LT = 2,5 days) to 'sprint truck' (alternative 2 with LT = 1,7 days). By this the overall LT of supplying is reduced from 5 to 4,2 days with the result that the range of coverage is now sufficient, because goods will arrive a day earlier and material shortage can be avoided (s. fig. 7).

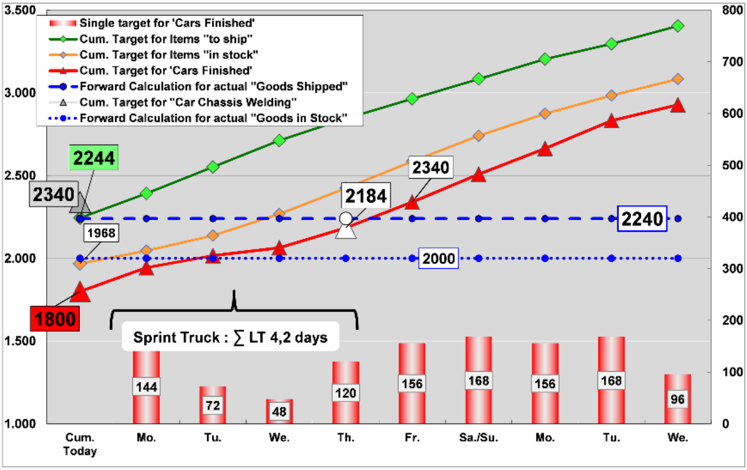


Figure 7: Delivery Process after Change from Truck-Tractor to a Sprint-Truck

The actual values for 'goods in stock' and 'goods received' matches with the values for final products (lower dotted lines) The actual QC of received components at CP 'GR' are in the defined range and the actual QC of components that have passed CP 'Sx' and are stored in the internal stock of the car manufacturer are in the accepted range too.

After this automatic change, an expert can analyze the situation in more depth and can initiate other countermeasures if needed e.g. permanent monitoring of transportation carrier or he can change the safety lead-time for the inhouse stock etc.

3.4.4 Distribution of Lead-time and Material Flow Balancing

In the example above we have calculated an average LT for the MF, but this is normally a stochastic process and therefore the LT is not a fixed value but has a certain distribution. The longer and more public the roads are, the more LT varies; there are also other influences like weather, traffic jams, road works, additional speed limits etc. Therefor we can estimate LT by a normal or a partially skewed distribution curve. Especially important are the minimum and maximum LT, for which we can define a certain sigma value level. The LTs are used for regulation of dominant and subdominant processes. Here we can discuss only some main aspects in general for two extreme scenarios:

1. Scenario: LT of the dominant process of product production gets the Min-LT and LT for the sub-dominant process of components gets the Max-LT, then the QC of components must always still higher than QP for products. If this condition is fulfilled, then stock-inventories of components will go down and safety-stock be consumed soon. Then the delivery process must be run very precisely and without any disturbances otherwise a material shortage will occur. For a safe delivery process, the Min-LT of products must be compared with the Max-LT of the dependent components.

2. Scenario: The dominant process gets the Max-LT and the sub-dominant process gets the Min- LT, then stock inventory of components will grow up so we need more space in the warehouses and also other negative aspects like higher storage and performance cost and more complication in material handling etc.

For this kind of planning we can use the same PMF-Structure, BoMs etc. but we must use other Control-data and chose other MFS etc. to find out critical scenarios and to balance order quantities of dominant and sub-dominant processes. For balancing we can also use separate control data about safety-stocks or alternative MFS for rule-based adaption of material flow and logistic processes. If problems further exist after process adaptation another 'Alert' or 'Warning' are issued and a new regulation can be started.

3.4.5 Logistics-Cockpit

For 'supporting' logistic regulation some further functions and tools are needed like a ‘Logistic Cockpit’ to visualize the actual state of the virtual and real logistic world and the results of analyzation deviation, especially to issue 'Alerts' and to initiate evaluation of data using different ‘Data-Analytic’ tools.

Logistic Cockpit: The Logistic-Cockpit is like a central tower or dashboard to visualize the planned and actual state of MFOs and to the results analyzation of deviations and combination with additional data and information (s. fig. 8). The Logistic-Cockpit shows at the same time the planned and real status of MFOs and issues Warnings and Alerts depending on the grade of deviations so the reaction can be differentiated by the DCT.

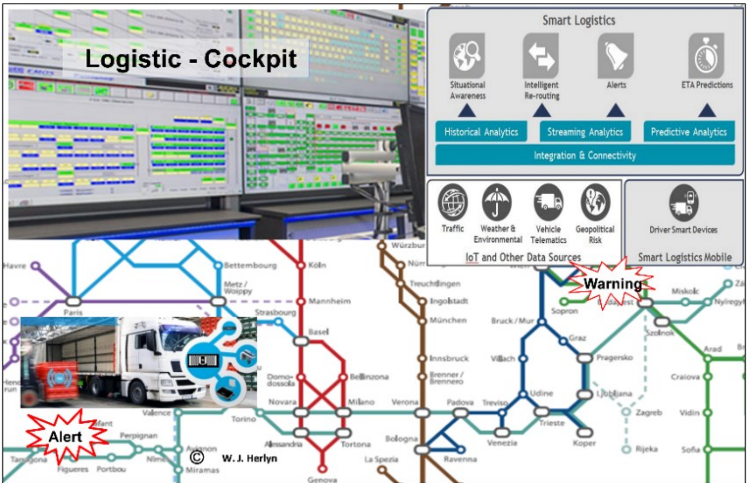


Figure 8: Logistic-Cockpit (exemplary show-case)

In case of an 'Alert' the Cockpit-Operator can zoom deeper into the 'problem' by changing the hierarchy level of PMF-Structure to get more detailed information. A prediction can be initiate what will happen in the nearest future if nothing changes. The operator can start a DA-tools to evaluate the situation or initiate a simulation to handle the problem in a different way. All of this is often called 'smart logistics'.

Data-Gravity-Center: The Data-Gravity-Center contains the complete history of all databases of the Repository and all results of DCT-Regulation including all values of Digital Trigger and Digital Shadows and all detected deviations and violations, alerts etc. The Data-Gravity-Center stores nothing else than the specific ‘Big Data’ of material flow objects and processes which can be exploited by ‘Data Analytics Tools'.

Data Analytics: Data Analytics means all kinds of 'intelligent' tools to exploit data of the Data-Gravity-Center e.g. to analyze passed deviations or to detect systematic problems in the process. We can use the grid and DA also for alternative planning scenarios using different control data (e.g. with Min-LT and Max-LT) to see what will happen or to react in case of accidents or unusual events to initiate counter-measures in advance. Also, optimization tools can be used to solve certain underlaying tasks in a shorter time than planning tool or is not able to solve, e. g. to calculate the actual sequence of transportation means for a Jit-Process for far distant suppliers (Schwerdtfeger et al., 2018).

3.5 The DCT-System-Controller and Execution Rules

Because the DCT-System is always 'on air' we need a regulation of the DCT itself which is like an Operating System of a conventional IT-System but works in another way.

Execution instructions and rules. They define at which metering point a "warning" is to be issued in case of a target/actual deviation, which data evaluation is to be triggered and/or which simulation tool is to be used to solve an unforeseen problem. This is one of the biggest differences to existing ERP-Systems where the different IT-Modules are combined outside each Module by Job-Control-Procedure (JCP) that interprets the 'Return-Codes' or 'System-Status' of a Software-Program. The intelligence of a Job-Procedure of a conventional ERPS must be imbedded into the DCT System. Because the DCT-System is always ‘on air’ all execution rules, cycle-times and procedure dependences must be imbedded. The execution is carried out by a System-Controller, which works in a defined time cycle by means of control instructions and rules. The control instructions, rules and cycles are stored in a database that is maintained by experts from the specialist departments and can be changed every time. Experts have to define at which CP which kind of 'Warning or 'Alert has to be issued by which grade of deviation. And, whether and which tool of optimization or simulation should be initiate to react on a certain predefined deviation. And special 'tools' can be started automatically if the DCT-System detects an unexpected event, an unknown situation, or in-logical data. And in addition different tools can be started by an expert if there are new logistics tasks or new technical or environmental requirements or if a problem occurs outside the System like jams, strikes etc. so the rules, the disposition parameters and other control data must be changed or adjusted. Rules and control instruction as well as the selection of the appropriate regulation algorithm depends on the LT and the time horizon of a certain MFS and the specific logistic task and purpose (s. fig. 9).

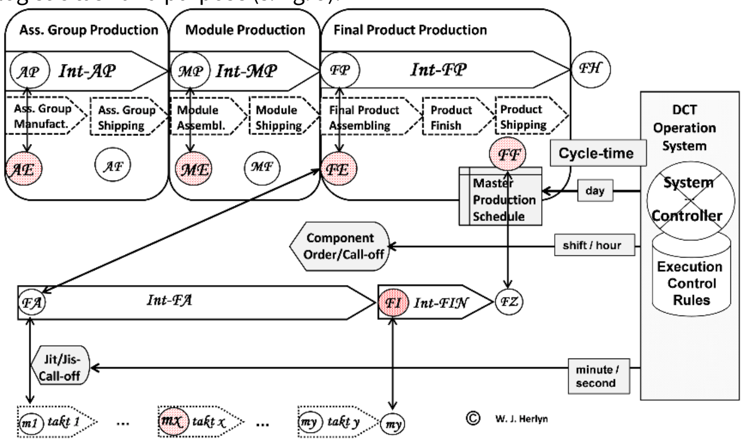


Figure 9: Different Logistic Tasks and Execution by Cycle Time

For example: The MPS will be started only once a day, while Call-offs for buy-parts are issued twice a day, and stock Call-offs for feeding of assembly lines are issued every 15 minutes and JIT Call-offs are triggered every minute. The instant information when an MFO passes a certain CP, e.g. a car entered the Final Assembly Line') is generated by an equipment, a processor of a machinery or asset itself.

In general: The choice of algorithms and tools depends on the concrete task and the lead-time corresponding and the reaction time which depends itself on the level of PMF-Structure. For mid-run planning of MF a 'upper' level of CP is suitable and for short-run planning a lower-level is suitable: e.g. ‘Master Production Schedule’ runs on the plant-level, ‘Assembly Line Schedule’ runs on assembly-line-level which is a certain area of production only and JIT-Call-Offs runs on the level of a 'takt'. Planning and monitoring of delivery depend also on different levels of PMF-Structure and the corresponding RT of transportation means. It makes no sense to calculate Call-offs for buy-parts every hour if RT of delivering from a supplier is about half a day or longer.

4 Some Requirements and Limitations for a DCT-System

The described 'DCT'-System has some inherent limitations for application under real conditions. The DCT is a closed system that can work properly only if the closured properties are not destroyed or confused from 'outside' factors. The DTC-System can be run only if the logistic reality has been mapped completely and exactly and match with the real entire logistic world. If this cannot guarantee always and for every factory, component, or supplier the DCT cannot generate correct results.

The DCT can be applied only for a set of familiar products which use the same PMF-Structure and BoM, there should be no overlapping in terms of PMF-Structure, PS etc. with other products or components otherwise and for these non-familiar products we need another separated DCT-System to control and monitor the supply chain.

The DCT can only be performed for completely defined final products and not for roughly defined final products which are normally used in forecasting scenarios. Only if actual customer orders are available in the MPS for a certain period the DCT can calculate orders for components and can compare and harmonize the real and virtual logistic world for this time-window according to the LT for the required components.

5 Summary and brief conclusion

The presented concept of a Digital Control Twin for mastering the supply chain is a response to new technologies and software-tools of Industry 4.0 and the huge amount of collected and available data of material flow objects because existing System bases mainly on the MRP-II concept which is able to react quick enough and don't use appropriate algorithm and methods for the industry 4.0 environment. The emergence and implementation of DT-Concepts for engineered products must be complemented by an logistic-oriented DT-Concept for material flow objects. This concept bases on three main pillars: reality, repository, and regulation, whereby Digital Triggers represent the virtual world and Digital Shadow represent the real world of material flow objects. Based on this fundament a DCT-System can be designed to regulate and harmonize material flow of final products and its dependent components across the production and supply chain network. Regulation as the kernel of the DCT-System is not static but dynamic because target-actual-deviations must be balanced permanently along a timeline. For order calculation of components and balancing of MFO's the method of closed-loop-control is used whereby Digital Triggers represent target values and Digital Shadows represent actual values. Target-Actual-Deviations are analyzed, and the DCT-System can choose one of alternative delivery or manufacturing routes by rule-based regulation. 'Alerts' are generated if actual values violate defined boundaries of target values which make it possible to intervene in the process or to initiate other tools like simulation or optimization. All data are immediately stored in an integrated specific 'Data Gravity Center' that allows experts to use new software tools for data analysis like data mining, machine learning etc.

The DCT-System is a self-regulated and the execution rules are stored in a specific database of a System-Controller. Real and virtual logistic data are permanently present. Real and virtual processes are performed parallel in defined time cycles so current and planned status of material flow objects can be compared in time and as required.

Because the DCT-System includes material requirement planning and order calculation a separate MRP-System is not needed in the short run planning as long as actual sufficient customer orders are stored in the MPS. By this the DCT-System can be integrated into the ERP-System and the MRP-Module for inhouse-parts and buy-parts.

The implementation of such a logistic-oriented DCT-System can start with only some components and then extended to more components and more complex logistic processes. Finally, the DCT-system must be included all major components of final products to master material low for production, supplying and distribution of a company.

The presented concept is still in an early stage, as a next step a protype of a DCT must be designed and tested to get experience for concrete products and material flow in a real supply chain environment.

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