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A modularised typology for flow design based on decoupling points – a holistic view on process industries and discrete manufacturing industries

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ABSTRACT

Management of production activities covers a wide range of decisions. In this paper, a modularised approach is suggested that, through configuration, generates a case-specific flow design. The approach is based on identification of decision categories that are generic and fundamental in the flow design, covering both discrete manufacturing industries and process industries. Each decision category identifies a unique property of the flow which changes at a particular point: this is termed a ‘decoupling point’. A three-dimensional modularised typology is developed by combining three different decision categories. Cases from the steel industry and the tooling industry are used to illustrate how the typology can be applied. The modularised approach provides a typology for the application of both qualitative and quantitative methods for flow management, including planning, control and performance management.

1. Introduction

Globalisation, shortened product life cycles and the increasing cost of manufacturing have shifted more emphasis onto the design and analysis of supply chains (Beamon 1998; Garcia and You 2015). Design is a key activity since it sets the baseline for the execution of activities in the supply chain. By carefully considering the preconditions for these activities, it is possible to increase both effectiveness and efficiency, not just in the performance of individual activities but also for the supply chain as a whole if a holistic approach is used in the design. During the design phase, the conditions for the transformation flow through the activities are defined; hence, it also provides the preconditions for planning and control of the different entities in the supply chain. The design provides the framework for integrating different planning issues related to for example strategic and tactical levels. It also concerns configuration and allocation of resource capacities, based on products, processes and customer markets (Goetschalcks and Fleischmann 2008). Consequently, supply chain design is a very challenging task as the number of decisions to be made is huge and each decision provides numerous alternatives. The designers involved must, to some extent, trust their combined experience developed from similar tasks, but important support could be provided if the key decision categories would be identified and a clear decision context defined.

Despite this inherent flow orientation, supply chain design is frequently approached from a geographical perspective, in which the physical aspects of the sites and the connections between them play a critical role (see, e.g. Mello, Semini, and Haartveit 2012). In this context, the components used reflect the different types of sites, available transportation modes, locations of customers and suppliers, etc. These ‘physical’ aspects are important, but, as highlighted by Wikner (2014), the fundamental flow logic of transformation provides additional information about key decision categories, for specific decision criteria, on how to design a supply chain from a flow perspective, based on the preconditions of supply and demand. A typical flow-based decision category is ‘flow driver’ associated with the decision criterion ‘driver’, which could be related to speculation on future customer orders or commitment to actual customer orders. Using this approach, consideration of the physical properties (related to physical transactions) and the legal aspects (related to financial transactions) of the supply chain are subordinated in the analysis to primary focus on the fundamental flow logic. The term ‘flow logic’ refers to the value-adding transformation being performed in the studied system and, in particular, the generic properties of the flow making it applicable to not only different flow patterns, such as different layouts, but also to different industries. In more traditional approaches to supply chain modelling, a set of different flows is usually identified, such as physical, information and financial flows. These aspects are also represented here but are related to system perspectives (legal, physical and logical), with different aspects highlighted depending on the perspective, of which each represents a level of abstraction that emphasises particular properties. First, the physical perspective highlights physical properties of the system and the key aspects of information flow. Second, the legal perspective emphasises the financial flow. In this sense, the legal perspective is a financial reflection of the physical flows and relevant information flows. Finally, the logical
perspective represents the fundamental flow logic where the
genital and physical properties are not directly considered. In this
sense, the logical perspective captures the characteristics of for
example the product flows and the information flows that are key
to the fundamental flow logic of the system. For example, there
may be manufacturing, distribution and transportation involved
in customer order fulfilment, but from a logical perspective, these
different types of physical transformation are simply aggregated
to a process triggered by a customer order. Once the fundamental
flow logic is identified, the next step is to also consider the physical
and legal aspects that may provide additional constraints on the
flow. The intention here is, therefore, to uncover the fundamental
flow logic as a foundation for analysing key characteristics of the
complete system, which also covers the physical and legal aspects.

The purpose of this paper is, therefore, to define a typology
based on the flow logic that provides a generic approach to flow
design supporting, for example planning and control in different
industries. The method employed in this research is principally
based on logical reasoning using input from previous research
literature related to the decoupling theory (e.g. Wikner 2014),
planning and control in the process industry (e.g. Pool, Wijngaard,
and van der Zee 2011), and more generic planning processes,
such as sales and operations planning (e.g. Noroozi and Wikner
2013). An important objective throughout the work has also been
to integrate concepts from the process industry (PI) with concepts
denoting the discrete manufacturing industry (DI).

The paper continues with a methodology section. Subsequently, the paper is essentially split into four parts. First,
the individual dimensions, i.e. the decision categories, of the
typology are outlined and investigated separately. Second, the
two dimensions are investigated pairwise, providing a baseline
for the typology. Third, the typology is defined as a set of inter-
sections between the three dimensions (as illustrated in Figure 5);
finally, the typology is applied to two cases to illustrate its poten-
tial practical application.

2. Methodology

This paper aims to define a typology focusing on flow logic that
is fundamental in the design of a supply chain in a production
and logistics context. According to Meredith (1993), taxonomies
and typologies are part of conceptual research methodology.
These two concepts are closely related where taxonomies are ‘listings of items along a continuous scale’ (Meredith 1993) and
typologies include two or more taxonomies on different dimen-
sions. The three dimensions, i.e decision categories, of the sug-
gested typology in this paper are: object type, control mode and
flow driver. The three dimensions are based on the transforma-
tion performed where objects are transformed by the system,
employing a control mode based on specific drivers originating
in the market. The dimensions have been chosen through the
review of related literature which, according to Wacker (1998),
aims to provide a new insight into the field through logical rea-
soning. The typology is also applied in two case companies to
show its applicability. A key aspect of the typology is that it cov-
ers both PI and DI; hence, the selected illustrative cases involve
continuous production and discrete production in combination,
i.e. both object types. Of course, the typology is also applicable
when only one of continuous production or discrete production
is present and, therefore, only one object type is involved. The
first case is a steel company drawn from prior research. Since
the steel company’s discretisation decoupling point (DDP) (the
point at which the object as a continuous material is turned into
a discrete, countable material) is positioned at the beginning of
the production process, both types of object are important. In
addition, this type of company deals with segmented supply
chains due to its diverse products and processes; therefore, it
has relevant illustrative characteristics to demonstrate the prac-
ticability of the typology. The second case is a tooling producer
although not customarily considered a PI company, it has a pro-
duction process similar to PIs, i.e. it actually has a DDP that is
also positioned early in the production process. The second case
company, therefore, has also been chosen to emphasise the
flow-based definition of PIs adopted in this paper, contradict-
ing the traditional industry categorisation based on the product
type, such as the food industry or pharmaceutical industry.

3. Frame of reference

This section provides a review of selected literature to provide
an overview of different classifications and design aspects
of manufacturing-based systems and their related planning
approaches. Through this review, a gap in the literature is
identified which is then used as the basis for introducing the
suggested typology in this paper. It should be noted that the
principal focus of the typology is to provide a platform for plan-
ning and control; hence, only papers with explicit focus on these
aspects are reviewed in this part. Consequently, papers focusing
on, for example manufacturing strategy, location allocation and
factory layouts are not considered comprehensively here.

As there are numerous manufacturing systems, there also
exist various classification types (Wild 1971) to facilitate better
understanding, planning and control of these systems (Porter
et al. 1999). Each classification, according to its purpose, com-
prises different dimensions, such as layout (see, e.g. Finch and
Luebbe 1995; McCarthy 1995); flow characteristics (see, e.g.
Arnold, Chapman, and Clive 1998; MacCarthy and Fernandes
2000; McCarthy 1995; Wild 1971); operational objectives/drivers
(see, e.g. Constable and New 1976; Porter et al. 1999); complexity
and uncertainty (Porter et al. 1999); or a combination of them
(McCarthy 1995). The dimensions and their interactions, in turn,
affect the planning and control of the production systems and
their relative supply chains (Finch and Luebbe 1995; MacCarthy
and Fernandes 2000).

In one of the early classifications, Wild (1971) divides the man-
ufacturing companies into continuous (bulk) and discrete items
producers. Wild’s classification is based on three dimensions:
production volume, product variety and repetitiveness. On these
bases, Wild classifies production systems into process, mass type,
batch type and jobbing type systems, where process manufactur-
ing is related to bulk products and the rest apply to discrete items
systems based on the material flow into four groups: continuous,
intermittent, project and pure inventory. Alternatively, Constable
and New (1976) define three dimensions: the nature of product
structure, physical flow system and the nature of the customer
order. They then discuss the planning of continuous systems,
assembly lines, and jobbing and batch production. Aneke
Carrie (1984) consider the following criteria for a flow line: number of products, number of operations per product, sequence of operations, whether set-up is required, whether production is in batches and the type of flow pattern. They postulated 16 production systems for the flow lines.

Finch and Luebbe (1995) make an important observation when they distinguish two types of manufacturing, namely discrete and continuous (non-discrete) manufacturing. They consider the material flow, routings, layout and volume as important dimensions in the process design and study the relationship between these dimensions, the manufacturing types and the level of customisation; on these bases, they propose a four-quadrant model: flow shops, continuous processors, job shops and batch processors (Finch and Luebbe 1995). MacCary and Fernandes (2000) consider four main dimensions: general characterisation (including enterprise size, response time, repetitiveness level and automation level); product description (including product structure, level of customisation and number of products); processing description (including types of buffer, layout and flow); and assembly characterisations (including types of assembly and work organisation). However, the decisive criterion for choosing the right planning and control system based on their classification is the repetitiveness level (MacCary and Fernandes 2000).

Finally, Strandhagen et al. (2012) suggest a control model based on decoupling point, control principles, operations areas, material and information flow, and main physical operations processes. They then suggest different planning and control approaches for different areas, comprising: just-in-time (JIT), kanban, constraint-based scheduling or theory of constraints (CBS/TOC), manufacturing resource planning (MRPII), project evaluation and review technique (PERT), and the critical path method (CPM). For a review of the different classifications, readers are referred to MacCary and Fernandes (2000), Porter et al. (1999) and McCarthy (1995). From an industry-generic perspective, one drawback with these classifications and their related planning and control systems is that, although they distinguish between discrete and continuous products, they either focus mainly on discrete products manufacturing or the planning and control approaches they suggest are mainly based on DIs’ requirements (see, e.g. Barber and Hollier 1986; MacCary and Fernandes 2000; McCarthy 1995). Nonetheless, these two types of manufacturing have various characteristics which affect their production planning and control systems (Dennis and Meredith 2000a, 2000b; Finch and Luebbe 1995; Taylor and Bolander 1994), and this is a strong argument for taking this distinction into consideration from a typology perspective.

In the context of PIs, Taylor and Bolander (1994) introduce the process flow scheduling (PFS) framework based on the process structure, rather than the product structure that mainly features in the above-mentioned classifications. In their framework, they consider production plans for divisions, plants, process trains, and stages and clusters. Respectively, they suggest cyclic planning, processor/material dominated scheduling and forward/backward flow scheduling. The forward/backward flow scheduling is usually based on the position of the constraint; Schragenheim, Cox, and Ronen (1994) develop this further by suggesting using the TOC to schedule PIs, since TOC connects production constraints to the market demand and decreases inventory levels.

Finally, Dennis and Meredith (2000a) classify a group of PIs based on their material diversity (including routings, equipment flexibility, flow, raw materials, ingredients and finished goods); materials movement (including inventory points, inventory profile, work centres and formulation complexity); equipment (including general purpose, specialty and product variety); and run time. On these bases, they identify three types and seven subtypes of PIs systems: intermittent types in terms of process job shop, custom blending and fast batch; hybrid types in terms of custom hybrid and stock hybrid; and continuous types in terms of multistage continuous and rigid continuous. In their other paper, Dennis and Meredith (2000b) classify the planning and control systems of PIs based on material requirements and consumption, capacity requirements and consumption, and material and capacity computerisation. They formulate the four groups of simple, common, work-in-process controlled, and computerised as the PIs’ production management systems (Dennis and Meredith 2000b). The group of PIs selected in both papers of Dennis and Meredith (2000a, 2000b) is limited to businesses in which the products are continuous and only become discrete at the packaging process. Hence, the PIs in which the products become discrete earlier in the production process, such as steel or textile companies, are not included in their study; consequently, their studies are not industry generic since discrete manufacturing aspects are not covered.

The references above cover the manufacturing-oriented structure and its relations to planning and control. An alternative is consideration of a more general and structural approach, in which Hoekstra and Romme (1992a) made an important contribution based on positioning of the customer order decoupling point (CODP) in the supply chain. Work on this approach was continued by, for example Giesberts and van der Tang (1992), Olhager and Rudberg (2002), and was then further developed into the customer order decoupling zone (CODZ) by Wikner and Rudberg (2005b) and the integration of multiple decoupling points by, for example Banerjee, Sarkar, and Mukhopadhyay (2012) and Wikner (2014). In general, a company has several flows, and hence several CODPs, since it has several distinct offerings to the market. The portfolio of product families targets different segments of the market with specific requirements of, for example, delivery lead times and customisation; hence, each segment may require uniquely positioned decoupling points.

As implied from the above review, different dimensions are considered by different authors as crucial for structuring the manufacturing systems and supply chains. The most cited dimensions are material flow (repetitiveness), CODP and product variety. The references are also alike in that, except for the few authors who merely emphasise continuous production, for example Taylor and Bolander (1994), the majority mainly develop planning and control methods based on discrete production characteristics, and only three of the references distinguish between continuous and discrete production and attempt to cover both. Thus, there is a lack of classifications which, in an integrative manner, consider the characteristics of both DIs and PIs. The intention of this paper is to fill this gap and to suggest a flow-based typology which is applicable in both DIs and PIs. As such, the typology is designed to provide a modularised design of the supply chain, or the individual entities of a supply chain, to provide a better...
understanding of, for example planning and control approaches appropriate for each module, to provide competitive advantages for companies that combine the selected modules through a configuration process.

Through the above review, following the work of Constable and New (1976) and in line with Wikner and Noroozi (2014), the suggested typology in this paper has three dimensions. However, to fulfill this paper’s purpose, definitions used for the dimensions are slightly different compared to the definitions in the literature above. The three dimensions of the typology are object type (see, e.g. Finch and Luebbe 1995; Wild 1971), which is related to the physical properties of the product; control mode (see, e.g. Arnold, Chapman, and Clive 1998; MacCarthy and Fernandes 2000; McCarthy 1995; Wild 1971), which studies the flow of material from the time perspective or repetitivity; and flow driver (Constable and New 1976; Hoekstra and Romme 1992a, 1992b; Porter et al. 1999; Wikner and Rudberg 2005a), which is related to the nature of customer order and forecast driving the flow.

4. The three dimensions of the typology

As outlined above, there are three flow dimensions of particular interest for flow design. The customer requests a product and that product’s properties are key for the supply. In particular, the type of object being transformed (i.e. discrete or continuous product) is crucial since it also affects the types of resources being employed in the supply process. When discrete objects are transformed in production, it is usually termed discrete manufacturing, defined by Blackstone Jr. (2010) as ‘The production of distinct items such as automobiles, appliances, or computers’. Discrete manufacturing is here termed discrete production and is performed in DI. The other large type of industry related to production is usually termed PI, defined by Blackstone Jr. (2010) as ‘The group of manufacturers that produce products by mixing, separating, forming, and/or performing chemical reactions’.

4.1. Dimension 1: object type

The object transformed in the flow can be of different types, which also affects the types of resources used in the supply process. Process manufacturing adds value by mixing, separating, forming, and/or performing chemical reactions. It may be done in either batch or continuous mode (Blackstone Jr. 2010). This means that the transformed object is of continuous type (Fransoo and Rutten 1994); therefore, we here term this continuous production as an analogy to discrete production. Consequently, an object being transformed in the flow can, at a given point in the flow, be either of continuous object (CO) type or discrete object (DO) type. When the flow object changes from CO to DO by, for example, packaging of a continuous liquid product to produce a discrete item, the preconditions for the flow change significantly; the point where this change occurs is termed a DDP.

DO is basically defined as an object that can be counted in pieces (Abdulmalek, Rajgopal, and Needy 2006). This type of object is handled individually or in batches. These objects are usually transformed individually, meaning that even if both production and transportation may be performed on batches, the objects can be transformed sequentially, i.e. in pieces.

CO cannot be counted in pieces but must be measured in terms of, for example volume or weight (Abdulmalek, Rajgopal, and Needy 2006). This means that CO cannot be handled individually, such as sequential transformation. Instead, they represent a ‘stream’, and the stream rate multiplied by a time period represents a certain amount (e.g. kg or m³), of the object.

Object type hybridity with DDP introduces an interface between the two object types: although they cannot themselves be combined, from a supply chain perspective the flow may be based on both types of objects; this is termed here object hybridity. Object hybridity is based on the assumption that a physical entity, such as a production site, can feature in the transformation of both COs and DOs. In general, DOs are not transformed into COs (Abdulmalek, Rajgopal, and Needy 2006). An example exception is when containers, which are discrete objects, of liquids are received and emptied into a CO-based flow. Otherwise, this does not tend to occur, and the most common scenario is when COs are discretised and, for example, packaged to become DOs. DDP is the point where the transformation of CO into DO occurs which creates an explicit association to decoupling theory (Abdulmalek, Rajgopal, and Needy 2006; Pool, Wijngaard, and van der Zee 2011, Pool, Wijngaard, and van der Zee 2011, Constantine and New 1976).
referred to this as point of discretisation). For the less common case of DO being transformed into CO, this could correspondingly be termed a continuisation decoupling point (CDP), but this is not discussed further here.

In general, both form transformation (production) and place transformation (transportation) within a network may be applied to both COs and DOs. Form transformation for COs and DOs would be continuous production and discrete production, respectively. Place transformation for COs can be conducted through pipeline transportation, while for DO it can be conducted through vehicle transportation. In this context, the network comprises physical entities as nodes, i.e. a network of production sites or distribution sites with transportation between the network’s nodes.

### 4.2. Dimension 2: control mode

The transformation control can be performed in different modes, ranging from a single occurrence in onetime mode (OM) to a continuous mode (CM). A compromise is the performance of recurring transformation; this is termed an intermittent mode (IM). The control mode basically refers to the planning and control approach that is suitable in a specific context and is related to, for example volumes required, frequency of requirements and the set-up time of the resources needed to change between different products. The control mode complements the object type, in that the latter defines a key property of the objects in the flow and the control mode represents how the flow of those objects can be controlled. This interaction is further described in the section below on cross hybridity between object type and control mode.

Wild (1971) was one of the first to use the terminology ‘continuous’, ‘repetitive’ and ‘intermittent’. Comparing the control mode to Wild’s classification, CM covers Wild’s notion of continuous, IM corresponds to both the repetitive and intermittent notions of Wild, and OM is partly covered by Wild’s notion of intermittent. OM has the lowest frequency/repetitivity level and CM has the highest level, which is consistent with MacCarthy and Fernandes (2000). IM is a compromise between the two extremes of OM and CM, and the control mode decoupling point (CMDP) is the interface between two different control modes employed in the flow.

OM defines the performance of a unique transformation. By definition, this type of transformation is performed once. ‘Once’ is, however, a relative concept here and is defined in relation to what is known at that particular moment in time. The same transformation may be performed later, but it is then related to demand that was not known, or expected, at the earlier occasion. It is also important to note that ‘onetime’ does not imply anything about whether one or more objects are being transformed at that time: it only implies that the transformation is being conducted on one particular occasion. Typical cases include, for example project manufacturing of large objects, such as buildings or customised manufacturing of unique items, such as heavy machinery, and the planning techniques used include, for example, PERT, CPM or critical chain method (CCM).

IM is applied when demand is recurring and CM is inapplicable. In most cases, this is due to significant set-up times that inhibit one-piece flow transformation in CM requiring frequent switching between different products. By transforming batchwise, the set-up time can be shared across the units in the batch to reduce the capacity required per unit and, consequently, also the unit cost. This is perhaps the most complex control mode, and the two sub-modes, in particular, may require differentiation even if they are still classified as IM here. The basic case, ‘closed batch’, is when the complete batch is transformed by a resource before any part of the batch is transferred to the next resource. The second case, ‘open batch’, relaxes this constraint and enables a smoother flow between the resources. In discrete production, the latter case is termed overlapping, and in continuous production, it is related to the use of campaigns. A standard approach is to use MRPII for the discrete case, but where capacity is critical, drum buffer rope (DBR) or PFS might be more appropriate.

CM is sometimes also termed one-piece transformation in DI. The OM is usually applied to flows of only one type of object or a set of objects acting as one virtual object type, where no set-up time is required for changing between the different types of objects within the set. This can involve different variants of a product family produced on a single line in mixed-model assembly, or single products produced in a sequence of resources in a PI. Most planning and control methods used for CM are rate based.

Control mode hybridity with CMDP separates segments of the flow where different control modes are applied. Transformation is assumed to be performed in one control mode at a time; therefore, the CMDP must be situated at an intermediate flow point, usually termed a stock point. As shown in Table 1, there are nine CMDP scenarios where an upstream control mode is combined with a downstream control mode. The three scenarios on the diagonal are void since they do not represent an interface between two different control modes and are, hence, categorised as ‘No CMDP’. It could, in some cases, be of interest to also indicate different types of, for example IM and in that case CMDP could also be indicated between two control modes that are the same but implemented in different ways. Note, however, that if the sub-modes of closed batch and open batch are covered explicitly, the intermittent case would be more complex as different subtypes of IM would be involved, but this is not included here. The remaining six scenarios all represent possible configurations. The OM–IM and OM–CM scenarios both represent the upstream onetime control mode changing into a control mode in which individual objects could be grouped and transformed downstream within the same set-up. It might be possible to identify some instances of these combinations, but, in general, they are unusual, hence they are in brackets in Table 1. Scenario IM–OM corresponds to when objects are produced under IM and then used in production under OM where, for example a product configuration is produced that is unique. This could mean that subcomponents are produced under IM (e.g. MRP-based) before the final assembly is produced under OM (e.g. CPM-based). Scenario CM–OM represents a similar hybridity, but here the subassembly can be produced in a continuous manner. The two remaining scenarios can frequently be found in different industries. The IM–CM scenario is frequently used in different lean settings where some form of final transformation, such as final assembly, is performed in CM within a product family on an assembly line. Some of the parts

<table>
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<th>Table 1. Control mode hybridity based on the CDP.</th>
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<td>Upstream OM</td>
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are provided using processes that require set-up times, such as pressing or forming, and hence act as ‘monuments’ using batch production in IM (see, e.g. Duggan 2012). Finally, scenario CM-IM is common in PI, where the initial transformations are performed as CM on some raw materials before the final stages, including both CD and DO, are performed as IM in, for example packaging. In summary, Table 1 provides an overview of different flow configurations of importance to selecting planning and control methods, regarding how to combine rate-based methods (suitable mainly for CM), time-phased methods (suitable mainly for IM) and network/pegged-based methods (suitable mainly for OM).

4.3. Dimension 3: flow driver

The control mode defines the key flow characteristics once the flow is activated. However, the actual activation of the flow is not covered there. The activation is termed here the flow driver, and, from a customer perspective, there are basically two possible types of activation, based on speculation on future customer orders, usually in terms of forecasts and commitment to actual customer orders (Giesberts and van der Tang 1992; Hoekstra and Romme 1992a; Pagh and Cooper 1998). The type of driver for a section of the flow in relation to the CODP is decided based on the relative lengths of the delivery lead-time and the production lead-time (Shingō 1989). Depending on the flow driver, the related processes can be associated to decisions based on the flow being speculation driven (SD) or commitment driven (CD), and the interface between these domains is the CODP (Giesberts and van der Tang 1992). In addition, there can be a combination of drivers, and this scenario represents a hybrid of the two, corresponding to the (resource based) CODZ (Wikner 2014).

SD flow is performed when the customers are not willing to wait for the delivery object. The supply flow is, therefore, driven by a forecast that estimates future customer orders (Hoekstra and Romme 1992a). The flow is performed based on speculation about future customer orders; as in all types of speculation, this involves risk-taking. A risk here is to not being able to deliver at the customers’ request, and this is handled by a stock point at the end of the SD flow. Risk management, in this case, is based on balancing availability with expected requirements for delivery objects, i.e. items to be delivered.

CD flow is easier to manage in the sense that the customer orders are known when the flow is performed. The properties of the requested objects are, therefore known, but, in this case, the risk is related to the resources that are used in the object transformation occurring in the flow. Risk management is, therefore, related to balancing availability with requirements for capacity of resources involved in the transformation to generate the delivery objects.

Hybrid driven (HD) flow is a combination of SD and CD, in the sense that, from a resources perspective, there is a mix of forecasts and customer orders. A typical instance is where one resource is involved in a combination of SD and CD flows.

Flow driver hybridity with CODP is obtained when a complete flow is managed and a set of flow configurations can be defined. In general, some part is always CD and based on customer orders. In make-to-stock (MTS) scenarios, only pick and pack activities are performed to customer order, but, in other cases, all form and place transformations may be conducted based on a customer order; this is, then, usually termed make-to-order (MTO). Note that, in both cases, administrative non-production activities, such as customer order administration, may also be involved. Even if SD and MTS have similar characteristics, they represent different perspectives. SD is the speculation driven part of MTS, but in addition MTS also covers the CODP positioned at the end of the flow. Correspondingly, MTO is not the same as CD since MTO also includes the CODP positioned at the beginning of the flow. Hence, MTS and MTO are configurations of the components SD and CD in combination with the CODP and as a consequence MTS and MTO are considered as hybridities. In some cases, engineering activities are also performed to customer order; when this is recognised, it is termed engineer-to-order (ETO). As a compromise between MTS and MTO the flow is decoupled internally, which is usually termed assemble-to-order (ATO), or finish-to-order (FTO) in Pls. Note that ATO then is a hybridity of SD (upstream of the CODP), the CODP and CD (downstream of the CODP).

5.1. Cross hybridity between object type and control mode

The control mode represents the repetitiveness of the flow, and is very important to consider when selecting the planning and control method. Figure 2 illustrates the possible cross hybridities between object type and control mode where the corresponding decoupling points are also indicated. All three control modes are suitable for DO and are frequently used; however, as shown in Figure 2, only two control modes are usually used in relation to CO because OM is rarely used in relation to COs. The main reason is that, in most cases, it is not profitable to produce
Each intersection in Figure 3 represents a unique decision context. For example, the intersection DO–SD represents the combination of two decision categories where discrete items are transformed based on forecasts. Correspondingly, CO–HD is typically within a PI where, for example, a liquid is produced based on a combination, hybrid, of forecasts and customer orders, and CO–CD is where all production is instead based on customer orders.

5.3. Cross hybridity between control mode and flow driver

The combination of control mode and flow driver is a baseline for planning and control. The control mode defines the basic planning and control approach, while the flow driver defines how forecasts and customer orders are combined, for example, master scheduling to define the total requirements. The nine intersections of control mode and flow driver in Figure 4 represent the possible combinations that can be used to configure a complete flow. With few, if any, exceptions, OM is only used for customer order-based flows (CD); therefore, the two additional combinations at the top of Figure 4 are dashed. IM can be combined with all three possible positions of the CoDP, as IM can be applied in batch production based on forecasts (SD), customer orders (CD) or a combination thereof (HD).

It is, however, important to note that in the case of IM, it is usually assumed that batches are used, which means that standard products or customised products for recurring customer orders are involved. If the products are unique for a customer order, the OM–CD combination would probably be applied for a unique delivery. Finally, CM can be applied for any position of the CoDP; hence, all three combinations are possible. In the two cases in which some or all of the flow is based on customer orders, it is a necessary requirement that the products belong to a product family for which there is negligible set-up time between the different variants in the family. In Figure 4, the control modes

Figure 2. Cross hybridity between object type and control mode.

Figure 3. Cross hybridity between object type and flow driver.

Above, some examples of methods for planning and control were indicated for different control modes. With this cross hybridity between object type and control mode further details can be identified. For DO, some examples of methods for planning and control are different types of network-based methods, such as CPM for OM, time phased approaches, such as MRPII for IM and rate-based techniques used in, for example, lean systems for CM. OM is, by definition, not as suitable for COs since they cannot be easily counted, and due to the characteristics of the process, the repetitivity is necessary to establish a competitive process as indicated above. Batch processing (IM) is, however, also commonly used for CO, and, of course, the CM is used in many PIs, where one single product is produced over an extensive time period, see, for example, PFS (Taylor and Bolander 1994).

5.2. Cross hybridity between object type and flow driver

The flow driver defines the CoDP that separates the CD flow from the flow with some level of speculation (HD and/or SD). A stock point will usually be positioned as a buffer at the CoDP since speculation involves risk (Hoekstra and Romme 1992a; Wikner and Rudberg 2005b). The HD flow is based on a combination of forecast and customer orders, whereas SD flow is only based on forecast and CD flow only on customer orders. In summary, this means that the CoDP is positioned at an inventory point between points of form transformation and/or place transformation. From a logical entity perspective (Wikner 2014), multiple CoDPs in sequence cannot occur in the same flow, even if they can occur in the same supply chain comprising multiple flows. Conversely, the object type can only be changed at a transformation point (Abdulmalek, Rajgopal, and Needy 2006), such as packaging. In general, a physical entity only has one CoDP and one DDP in a particular flow but may, of course, have several parallel flows and, hence, multiple CoDPs, for example, one per product family. By combining these two dimensions, six possible intersections related to cross hybridities between object type and flow driver can be identified as of Figure 3.
represent the flow through which the transformation takes place. The arrow of the flow driver symbolises that it provides the activation signal to the flow. For SD, it is usually a forecast or some form of plan, whereas for CD it is directly or indirectly an actual demand in terms of, for example, a customer order or a firm delivery schedule.

6. The typology

The typology developed here targets decision support for supply chain design, emphasising key characteristics of the flow logic. The three decision categories of object type, control mode and flow driver have been identified as fundamental for the typology. A particular decision may concern only one dimension, and then a hybrid is created between two different states of that particular dimension (such as forecast driven flow upstream of the CoDP and customer order driven flow downstream). Frequently, however, more than one decision category is significant and, in this case, a hybridity between two or three decision categories is necessary; this is highlighted by combining two or more dimension into so-called cross hybridities. Before modeling a particular supply chain, it is necessary to identify the complete set of different cross hybridities between the three decision categories, here termed modules of the typology. Thereafter it is possible to outline how a specific supply chain design can be identified as an ordered subset of modules through a configuration process.

First, the complete set is identified by combining the three two-dimensional cross hybridities outlined above. Assuming that the properties of each dimension are independent of the other dimensions, the set can be illustrated as a rectangular cuboid, or just ‘cuboid’ for short (see Figure 5). Each side of the cuboid represents the combination of two dimensions discussed above as two-dimensional cross hybridities. The cross hybridities of Figures 2–4 are consequently superimposed on the typology in Figure 5 to show how they are related. Each cross hybridity between two dimensions is illustrated on one side of the cuboid which represents two dimensions. The corresponding decoupling points are also positioned in relation to each dimension of the typology.

In total, the typology, illustrated as a cuboid in Figure 5, identifies that the complete set consists of 13 reference modules illustrated as dark gray boxes (excluding the dashed ‘boxes’, i.e. modules, in Figure 5). The next step is to identify the modules appropriate for a particular supply chain design by employing a configuration process to represent the supply chain from a flow perspective. The subset is ordered in the sense that the configuration is based on a flow perspective where the flow indicates the order, i.e. sequence, of the value-adding activities. Each module represents a well-defined state in terms of the three dimensions, but when two modules are in sequence, there is a flow transition from one state (one module) to another; this decoupling of the flow is crucial here as it represents the position at which the preconditions of the flow change, and, hence, is where the management approach for the system must be adapted. This approach of combining modules to a sequence is termed “creating an ordered subset” and is here related to configuration of the typology, where standard modules are combined to create a case-specific supply chain design.

The 13 reference modules each provides consistent preconditions in terms of object type, control mode and flow driver. It is, therefore, possible to, for example outline recommendations concerning appropriate methods for planning and control or a suitable set of performance measurements to be used for each individual module (see, e.g. Noroozi and Wikner 2016). In the next phase, a case-specific ordered subset is identified for a particular supply chain design, where a coordination approach can be defined as a combination of the recommended approach for each module that is included in the ordered subset. Two examples are provided below to illustrate how the typology can be used in actual cases. The objective is to identify an ordered subset of the typology that can be used as a point of reference for benchmarking the methods and measures actually used in the company for each module, with the recommended standard procedure associated with each module used in the design. The benchmarking step is, however, not included below, as the objective here is only to illustrate how the approach can be used to establish the ordered subset for each case.

7. Application of the typology in two cases

Two companies were chosen to illustrate how the typology can be applied in real cases. The intention here is to show how the typology can be used to configure a model based on the predefined modules of the typology. A module represents a well-defined decision context providing the preconditions for

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**Figure 5.** Modularised typology for flow design based on decoupling points.

CD: Continuous Object
DO: Discrete Object
OM: One-time Mode
IM: Intermittent Mode
CM: Continuous Mode
SD: Speculation Driven
HD: Hybrid Driven
CD: Commitment Driven

DDP: Discretisation decoupling point
CMDP: Control mode decoupling point
CODP Customer order decoupling point

Flow Driver

Control Mode

Object Type
the application of methods and techniques for, e.g. planning and control. The first case is a steel company, and the second is a tooling company, both of which are located in Sweden. The steel company is a PI with the DDP positioned at the beginning of its production process; due to its diverse products and processes, it has good illustrative characteristics for demonstrating all three kinds of two-dimensional cross hybridity. The tooling company, conversely, regards itself as a DI; however, on closer scrutiny of how it is managed and the properties of the products in the flow, it has several characteristics of PI. Its production process is similar to a PI’s in the sense that it has a DDP, which is positioned very early in the production process. This case emphasizes the importance of focusing attention on the flow characteristics rather than the traditional classification of a company as PI or DI. The application of the typology is illustrated in Figure 6 and Figure 7. In both cases, the property of each dimension is indicated on a side of each module. Assuming a transformation flow from the left to the right the decision category flow driver is indicated on the front of each module (SD, HD and CD). The decision category object type transformed in the system is indicated on the side facing the flow direction which then is to the right (DO and CO). The decision category control mode, finally, is indicated on the top of each module (OM, IM and CM) as it represents the management approach employed for that module. Previously, as in Figure 4, the flow driver was indicated at the top but for consistency with the background in the transformation flow, see, for example Figure 1, the three decision categories are illustrated on the three sides of each module as outlined above.

7.1. Case 1: steel company

The first example is based on the steel company described by Rudberg and Cederborg (2011). This company is a niche producer of high-strength steel plates, with brands such as Hardox and Weldox (Rudberg and Cederborg 2011).

The production process starts at the coking plant, where coal is converted into coke and gas. The coke is used in the next operation, i.e. in the blast furnace, where the iron ore, coke, limestone and some other additives are heated continuously until hot metal with the correct carbon content is achieved. The hot metal is then continuously fed into the torpedo cars. A torpedo car’s capacity is around 300 tonnes of molten hot metal. Both the hot metal and the cooling scrap are transferred to the LD converter, and then finely adjusted in the ladle surface; finally, in the continuous casting machine, the steel is converted to solid form and cut into slabs. These slabs are then left on cooling beds until they are ready to be transported to the rolling mills. These slabs weigh around 25 tonnes each: too heavy and thick to be suitable for the use of ordinary customers. Hence, the slabs are processed in the rolling mills to achieve the right size and thickness according to customers’ orders. The steel plates might later also undergo additional processing based on the customers’ orders, such as cold rolling, annealing, galvanizing and painting (SSAB Communication 2014; SSAB Public Relations Department 2014).

Comparing the steel company’s production process with the typology introduced in this paper, the DDP is positioned at the continuous casting machine, the CMDP is positioned at the torpedo cars and the CoDP is positioned before the rolling mills. The illustration at the top left of Figure 6 shows the three decision categories in parallel, but with the relative positioning of the decoupling points in the flow indicated, for example the DDP is positioned upstream of the CoDP. On the right in the figure, the modules of the suggested typology are illustrated as a combination of the three decision categories, with the identified modules indicated in orange (N.B. the dark grey modules are not selected). At the bottom left of Figure 6, the identified modules are outlined in sequence, i.e. an ordered subset, as an illustration of the configuration of the flow and, hence, representing the design of the supply chain from a flow perspective. The product flow is from left to right and the change in each step from the previous is shown by the red text on each module, with the corresponding decoupling points identified between the modules. For the steel company, the production process contains several demanding
steps, but the typology provides a management perspective of the process that enables benchmarking of the flow that was not obvious when only the more technical details of the flow were highlighted. This is a typical result for technology intensive environments, which also tend to be technology dominated as regards management decision-making.

7.2. Case 2: tooling company

The second example is a tooling company which is a producer of metal cutting tools, including milling, turning and hole-making tools (SecoTools 2014). The products are mainly constructed from cemented carbide. The main raw material used is ammonium-para tungstate (APT), which undergoes a process of dissolutions, precipitations and separations. Pure tungsten powder is obtained from the heated reduction of the APT in hydrogen. Tungsten is then mixed with carbon and heated at a high temperature in hydrogen to obtain tungsten carbide powder. Tungsten carbide is then mixed with binder cobalt and other additives, before the mixture is wet milled. The milling process affects the grain size and homogeneity of the slurry, which is dried through a spray-drying process through which the tungsten carbide powder is formed. This powder is pressed into compacts in the compaction process. The compacts are soft machined or green shaped into a proper shape if required, before being sent to the sintering process, where the cemented carbide obtains the properties of a high strength material. Sintering is conducted at a very high temperature so that the molten binder can combine with the tungsten carbide. During the sintering process, the compacts shrink to around 50% of their initial volume and are usually sent to the machining process prior to shipping (Sandvik Hard Materials 2008).

The production is batchwise and the products are mainly MTS. Comparing the production process to the typology, it may be observed that the DDP is positioned at the compaction process where the powder turns into compacts. Since the same control mode is applied throughout the flow, there is no CMDP positioned within it, and the whole production is batchwise (IM). The CODP is positioned at the finished goods inventory, consistent with the company’s MTS strategy. The positions of the decoupling points are shown in Figure 7; even if the manufacturing process is inherently complex from a technological perspective, the typology reveals that from a flow design perspective, there are actually only two modules involved in the ordered subset. For the tooling company, the typology highlights similarities with PIs that were previously not identified. Based on this insight, benchmarking can be made against companies not previously considered to be similar.

8. Discussion and managerial implications

Supply chain design provides the preconditions for planning and control; however, it has received relatively limited attention compared to the vast array of methods available for actually performing planning and control. In most cases, the design is based on the physical properties of the supply chain, but, as outlined here, a typology founded on flow properties provides a complementary perspective. The flow-based typology for supply chain design outlined here is based on decoupling points and a set of standard modules that each represents a well-defined state. In practical application, the modules are used in a configuration process to establish a customised flow model in terms of an ordered subset of modules. The transition between the modules corresponds to decoupling points in the flow and should be given particular attention in the design process. As demonstrated in the cases of the steel company and the tooling company, the configured models in Figures 6 and 7 exhibit some of the core characteristics of the systems; hence, they provide important insights for the design of planning and control based on a case-specific configuration of standard modules. The derived models not only highlight key characteristics of each system but also provide great support for benchmarking of, for example, planning and control, and performance measurement systems through the 13 reference modules. Applying the typology in this fashion is based on the modules that each have consistent properties in terms of the objects being transformed, the control mode applied in the transformation, and how forecasts and customer orders are combined as the driver of the transformation. Each module, hence, represents a stable state for selecting appropriate methods for managing that module. This could involve decision support on which techniques to use for optimising the flow in that module and what performance measurements to use. The typology implicitly suggests a two-level hierarchical approach, in which the ‘low’ level is the individual modules and the ‘high’ level is the configured set of modules, which illustrates that a modularised approach to planning and control can be employed based on the typology. By defining a recommended set of tools for each module, the actual configuration provides for customisation in the sense that the configuration is specific to a particular case but still based on a set of ‘standard’ modules. In retrospect, the cases of a steel company and a tooling company used as illustrations may seem obvious and the modules straightforward to identify in these cases. This apparent simplicity of handling the cases should be attributed to the convenient application of the typology rather than to the cases per se being simple. With this generic approach, it is possible to establish a collection of methods applicable for each module in a generic fashion, rather than applying an ad hoc approach through which the methods are applied at the discretion of the designer, based only on that designer’s previous experience. Noroozi and Wikner (2016) applied a derivative of this typology to a sales and operations planning context which is an illustration of the usefulness of the typology.

9. Conclusions

Although the three dimensions of object type, control mode and flow driver have been included previously in different frameworks for supply chain design, the approach outlined here provides a new way of employing a modularised approach based on industry generic modules. The typology can readily be extended to more dimensions if required. The modularised approach to configuration-based supply chain design is founded on three different decision categories that represent three dimensions of the typology. A key property of the typology is its applicability in both DIs and PIs, since the product properties are considered in terms of the object type. The object type is, hence, the first dimension and represents materials and the
transformation performed. The object type also implies which types of resources can be employed in the flow related to the particular object type. Transformation of discrete items differs fundamentally from the transformation of continuous materials, such as liquids. COs require certain properties of the process since no individual objects can be identified. DO, conversely, is by definition individual objects that can be handled sequentially in both form and place transformation. The second dimension, control mode, represents the opportunities available for managing the flow due, in particular, to preconditions related to set-up time, combined with demand properties. In this context, it is important to again note the implicit resource perspective and the relation to set-up times. If different objects can be transformed in arbitrary sequence, meaning that negligible set-up times are required, the transformation can be performed in CM. On the other hand, if the set-up times are significant, the control mode is IM, whereas where the transformation is performed only once, the control mode is OM. The third dimension included is the actual trigger of the transformation, termed here the flow driver. This represents why the transformation is being performed, whereas the control mode represents the conditions for the transformation and the object type that is being transformed. These three decision categories in combination provide key information during the design process for identifying appropriate methods for planning and control. Consequently, the modularised and configuration-based approach to flow design provides an opportunity to apply qualitative and quantitative methods in a more effective and more efficient way. The approach also emphasises more fundamental aspects from a management perspective than classifications based on, for example, different types of industries. In particular, the modularised typology establishes a foundation for development of hierarchical methods of flow optimisation that exploit the flow-based structure of the models, where the appropriate ordered subset is identified based on the complete set of 13 reference modules.

An obvious extension of this typology would be to also explicitly include level of customisation as a separate dimension to complement the flow driver. In its present form, the typology’s modules do not distinguish between standardised and customised objects. In addition, other dimensions may be included related, for example to services and return flows. The assignment of proper planning and control methods to each module is an additional venue for further research, in which the typology could provide a point of reference for the application of both qualitative and quantitative methods using a configuration approach based on rather standardised modules, resulting in a modularised approach not only for supply chain design but also for supply chain optimisation. More comprehensive implementation of the typology in real case companies should lead to further refinement of the typology, in addition to better alignment between each module and the related planning and control methods.

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References
Appendix 1.

Some key abbreviations used in the text:

<table>
<thead>
<tr>
<th>Abbreviation</th>
<th>Description</th>
</tr>
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<tbody>
<tr>
<td>ATO</td>
<td>Assemble to order</td>
</tr>
<tr>
<td>CD</td>
<td>Commitment driven</td>
</tr>
<tr>
<td>CDP</td>
<td>Continuous decoupling point</td>
</tr>
<tr>
<td>CM</td>
<td>Continuous mode</td>
</tr>
<tr>
<td>CMDP</td>
<td>Control mode decoupling point</td>
</tr>
<tr>
<td>CO</td>
<td>Continuous object</td>
</tr>
<tr>
<td>CODP</td>
<td>Customer order decoupling point</td>
</tr>
<tr>
<td>CODZ</td>
<td>Customer order decoupling zone</td>
</tr>
<tr>
<td>DDP</td>
<td>Discretisation decoupling point</td>
</tr>
<tr>
<td>DI</td>
<td>Discrete manufacturing industry</td>
</tr>
<tr>
<td>DO</td>
<td>Discrete object</td>
</tr>
<tr>
<td>HD</td>
<td>Hybrid driven</td>
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<tr>
<td>IM</td>
<td>Intermittent mode</td>
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<tr>
<td>MTO</td>
<td>Make-to-order</td>
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<tr>
<td>MTS</td>
<td>Make-to-stock</td>
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<td>OM</td>
<td>Onetime mode</td>
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<tr>
<td>PI</td>
<td>Process industry</td>
</tr>
<tr>
<td>SD</td>
<td>Speculation driven</td>
</tr>
</tbody>
</table>


Wikner, Joakim, and Sayeh Noroozi. 2014. “Typology for Planning and Control – Combining Object Type, Mode Type, and Driver Type.” International Conference on Sustainable Design and Manufacturing, Cardiff.
