Developing a Production Structure Model using Service-Dominant Logic – A hypergraph-based Modeling Approach

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ABSTRACT

To make a fundamental shift towards value orientation, manufacturing companies strategically move to integrate services into their portfolio. While manufacturing firms rely on production information systems as the backbone of their operations, these systems are based on product structure models (e.g., bill of materials). This poses a problem because services do not adhere to the goods-dominant perspective of product structures. To solve this divide, this paper proposes an integrative mathematical model for both production systems and service systems. This model draws upon concepts of service-dominant logic and is based on hypergraph theory. To illustrate that the production structure model includes both product structures and process structures, we further demonstrate that the production structure model can be transformed into either. Therefore, our theoretical contribution lies in introducing a structural model for production systems that is compatible with structures of a service system model. For practice, this model enables the development of production information systems that can plan and control products, services and hybrids.

Keywords: production service system, service systems, production structure model, production graph, product structure, process production structure, hypergraph model of production structure

1. INTRODUCTION

Since the 21st century, services have steadily gained importance, playing an increasingly larger role for the world economy [1]. As of 2017, approximately 63% of the worldwide GDP originates from the service sector, while only 30 % stems from the industry sector. Consequently, the widely accepted idea of service-dominant logic (SDL) emerged [2]. SDL considers production-related issues as relevant and addresses the traditional characteristics of being immaterial or not as a distinguishing factor for services by introducing the concept of operand and operant resources. Hence, service-dominant logic treats products as goods that transport value for customers. SDL covers the entire economic spectrum, including both the service sector as well as the industry sector.

Services are primarily non-goods-reliant, such as digital services or knowledge-intensive services, and exclude issues of production [3]. Although there are product service systems (PSS) that rely on products or on how to incorporate services into an existing product portfolio as means of an added-service, they look at service as a tool to identify business model innovations [4]. It is primarily servitization research that looks at traditional goods-dominant production to make inferences on how to transform goods-dominant organizations (e.g., manufacturing) into a service-dominant perspective in hopes of improving their business model [5,6]. Despite the claim, that service-dominant logic is applicable to goods-dominant logic issues, it remains open how service logic can be integrated and meshed into traditional production structures and vice versa. In this paper, we aim to move towards an SDL perspective on production by introducing a production system structure that is compatible with the structure of service systems.

Following the service-dominant logic perspective, a mathematical model for service systems has recently been introduced [7]. Its hypergraph-based service system graph (SSG) is a step towards operationalizing service-dominant logic [2] and particularly its views on service systems [3]. Service and production are both transformation processes of resources [8]. One of them is done by operant resources as acts and another is done by supplement resources, such

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as operation equipment and assets. A significant difference between service and production is the resource characteristic. For service, research often focuses on the immateriality of its resources, whereas in production the focus is on material resources. Furthermore, existing process models and product structure models are the foundation for modern production information systems (e.g., ERP systems). Yet, it is apparent that product structures (e.g., bill of materials) are not suitable for modeling service systems. For therein lies our overarching research goal: to find a common mathematical form to model both service systems and production systems. To move towards our research goal, in this paper, we apply its formalization approach, its underlying mathematical logic of using hypergraph theory and mappings to develop a production graph to model production systems [9] and production structures in particular.

By using one integrative model, future engineers are enabled to model systems that include both production and services, more precisely and clearer, paving the way for a quantifiable service-dominant logic perspective for service systems and production. Additionally, for production systems, product models are essential because of their important role across functional areas of product lifecycles [10,11], including but not limited to design, purchasing , inventory management, planning and scheduling and logistics [12–14]. Due to the wide acceptance of product models and their importance for production and, more importantly, to demonstrate our production structure's wide applicability, this paper will conclude by deriving product structures and process structures from the introduced production structure. This intends to demonstrate that the production graph/production structure is compatible with existing product models and its models (e.g., bill of materials/BOMs).

This paper thus seeks to answer the question of *how to represent production structures as foundation models for application information system so that they are compatible with service system structures*. To explore this question, the paper starts with a brief related work section, which outlines characteristics of the service-dominant logic perspective and the mathematical service system graph as base models for service systems. Then we introduce contemporary product structures for manufacturing systems. The next section introduces a mathematical model of production structures, which describe the production's factors and their relations, including raw materials, operating equipment, other assets and processes. This model differs from previously introduced product structures, which describe the relations between a product and its composition. The next chapter introduces the application of the production structure, which shows that traditional product structures can be induced as subgraphs from production structure graphs and it also shows how the mathematical model of production structure can additionally be an induced subgraph for a process flow model. Additionally, we explain the versatile role of functions within the production structure application. The paper concludes with a discussion and future work section on the three major contributions of our production graph: 1) conceptually integrating production into service, further diminishing its divide, 2) showing the usefulness and versatile application possibilities of a production structure regarding product models and 3) providing a common mathematical model for both production structures and service system structures.

2. RELATED WORK

In this section, we briefly review our underlying perspective of service-dominant logic [2] and corresponding service systems, a recent mathematical model for service systems represented as graphs. Secondly, in order to explore and model production systems, we first introduce how the structure of products is typically represented in industrial engineering and manufacturing [12,14]. Then the process models will be described briefly because both of them are used as items compared to the production structure to show that they are contained within it.

2.1. SERVICE-DOMINANT LOGIC & SERVICE SYSTEM MODEL

Service-dominant logic exists in relation to goods-dominant logic [2]. In the traditional goods-dominant logic, a typical manufacturing process consists of resources that are transformed, such as raw materials, plus factors which are needed for the transformation but are not transformed themselves, such as equipment, tools and workers. Depending on what is to be transformed, the resources that are transformed could be either physical attributes of the resource (e.g., manufacturing) or transformed by moving the resources to other locations (e.g., logistic). Furthermore, a transformation of human resources can occur through physical changes (e.g., healthcare) and also through changes of the mind (e.g., mobile learning and entertainment services) [15]. In each example, the conditions of certain resources were transformed while some resources were not affected by the transformation [8]. We acknowledge the operand and operant resource perspective and integrate both types of resources into our understanding of service as transformation of all input factors into the output factors [15], also known as value proposition [16].

Complimentary to our service as a transformation process perspective, research on service science regards the service system as its basic unit of analysis [3,17,18]. All constituent factors of a service system and its interrelations make up a service system's structure, which is defined mathematically using hypergraph theory [19]. The service system structure is also known as service system model (SSM) and its graph is known as service system graph (SSG), The equivalent of a service system structure would be a production system structure that encompasses both process structure and product structures. The production system structure is a synonym for production structure and is the key contribution of this paper. Furthermore, it is exactly its mathematical underpinning that enables the compatibility with service system structures.

More precisely, constituent factors of a service system are **actors** utilizing operand and operant **resources** [3], whose **activities** describe the "transformation process". Actors can be individuals, teams, organizations, cross-organizational business units or even systems, as long as they mobilize required resources. This mobilization includes conceptual actors that describe any additional restriction in the resource configuration. A formal model for the structure and composition of service systems has been introduced, which can model the relationships of all resources and activities of services and corresponding service systems [7,19]. However, their model is not applicable to product models. Therefore, we define a production graph for modeling product structures and its accompanying process structure.

2.2. Structures of Products & Process Models

The goal of this paper is to introduce a production graph as a structure model that covers both product structures and process structures. To understand how a mathematical model can replace product and process structure models, this subchapter briefly introduces what a unifying production structure would include.

To model structures of products, it has been generally accepted to use BOMs (bill of materials) for the composition of products. They list the components that are required to produce a specific product, such as parts, subparts/assemblies and products, variants and alternatives and its relationships [20]. The typical bill of materials is based on a tree structure and a collection of BOMs define the product structure. Furthermore, product structures are used in conjunction with process models that explain how specific product structures are made, by detailing each step that is required and captures the required sequence of activities, while considering the information of the product structure. Therefore, BOMs are fundamental for planning and scheduling production and contain information on the quantity of each required part, which is used to assess further planning and scheduling tasks [21,22]. The product model is therefore used across the entire product lifecycle management, spanning from product design [23], production [21,22], inventory [24] and supply chain and logistics [25]. Any viable production must therefore be able to have the required information of a given product structure.

The process model of the production process corresponds to the product structure and must be established in parallel. Based on diverse requirements, such as time, cost and quality, both models are required to collect the necessary data to find possible production pathways, such as optional or alternative sequences and material requirements for a product. To model the activities into production processes, different modeling approaches and tools are available, with BPMN and Petri-nets or variants thereof being widespread [26,27].

3. Production Structure

The purpose of this section is to model production structures, which describe the relations and the combinations of various resources such as input material, operating resource, such as equipment, assets and other necessary things, and the technology process (plans, know-how) to make something for consumption (as output). Usually the production structure model is built by two models separately and work together for application; one of it is the product structure model, often used to plan materials, and another is the process model, usually for planning the use of equipment. In our research, an integrated model for the production structure is developed to regard the more efficient application optimization, which integrates both product model and process model.

3.1. Resources, Actor, Activity

Resources in the service-dominant logic represent the required production factors [28,29]. Some resources are soft and intangible things, such as skills and knowledge, whereas other resources include both materials and manufacturing machines. They can consist of single materials, a set of materials or parts, modules and collection of resources. Yet, as resources can be applied to other resources in order to create value [29], it is beneficial to distinguish between ***subject resources*** and ***supplementary resources***.

Subject resources are needed for creating value and are subject to value-creation itself, changing its own form in the process [28]. For example, during production, raw materials are changed into refined materials, adding to its value.

This entails changing the very form and nature of the resources, the same holds true for parts that get assembled into products, forming a new entity. However, supplementary resources are also necessary for value-creation, yet are not subject to the transformational process [8]. A classic example of supplementary resources is operating equipment, which is required for many manufacturing processes but does not get changed during manufacturing. Other factors often include capital intensive assets such as land, which are non-deprecated after its use, and deprecated assets, such as machinery, plants, building, factories etc., all of which have in common that they do not transform their own characteristics during production. Operand resources are therefore usually subject resources (e.g., material), whereas supplementary resources can include operand (e.g., machinery) and operant resources (skills and knowledge).

An actor is used to describe the executor of an action, that is to say, an actor is an entity that makes use of relevant resources to complete an activity. In the context of production, production equipment, including plant, business premises and so on can be regarded as actors. Activity is a general term describing the process of resource transformation.

3.2. PRODUCTION GRAPH

The previously introduced elements of interests can be modeled as either actors, resource or activity using hypergraph theory because, in accordance to [30], hypergraphs can be ascribed three meanings: to vertices, hyperedges and the entire hypergraph. As we introduced, there are two types of input variables that are relevant for operations: subject resources and supplementary resources. Additionally, following SDL, actors, activities and objects need to be defined in a rigorous and formal matter. This chapter will model a production graph using hypergraph theory, to define the interrelations of all five terms and represent the value creation structure for production.

In mathematics, the generalization of a graph is called a hypergraph. A hypergraph $G=(V, E)$ exists as a pair of edges E and set of vertices V, where the edges $e \in E$ do not only connect two but any number of vertices $v \in V$, thus calling E a set of hyperedges. A hyperedge $e \in E$ is therefore a subset of all vertices V, which are connected by it, $e \subseteq V$. Additionally, E is a subset of $P(V)\backslash\emptyset$, where $P(V)$ is the power set of V.

Taking the input-output perspective, operating consumables can either be parts that get assembled and consumables that get “used up”. Either way, after operations, at least one part with increased value gets produced (sometimes excess waste as well, but usually it is not part of planning). Both parts and consumables are modeled as hypergraph vertices. Thus, we replace $v \in V$ with resources $r \in R$. We define actors $a \in A$ as the hyperedge of R, replacing $e \in E$. As mentioned, assets and a set of resources represent a form of unit that shows a logical high-cohesion. We name the unit of actors and resources as product objects. Hence, product objects represent all required input factors for operations. We define product objects as follows:

Definition 1: A finite non-empty set O_P is called product object denoted by $O_P=(R;A=(a_i)_{i\in I})$ on a finite set R of resource is a family $(a_i)_{i\in I}$,(I is a finite set of indexes) of subsets of A called actor which $a_i \neq \emptyset$ and $R=\bigcup_{i=i\in I} a_i$.

This definition shows that a product object is a hypergraph. Set $A=(a_i)$ describes all combinations of resources in production, with subset a_i representing a logical relation describing the cohesion of a group of materials for a specific product or part. This is very much in alignment with the general principles of object-orientation, in which objects reflect a functional cohesion [31]. Apart from the required resource, to create value, we still need to define production functions that incorporate the transformational process. This approach applies to hypergraph theory, similar to how [7] applied the mathematical approach to service systems. They provide the value-addition for resources, while using supplementary resources.

Definition 2: Given hypergraph $O_p = [R, A]$ as set of product objects with resource set $R\neq\emptyset$; actor set $A\neq\emptyset$ and mapping $\Psi(\Psi^-, \Psi^+)$: $O_p \rightarrow O_p$, where $\Psi^-(O_p)\cap \Psi^+(O_p)\neq \emptyset$ and $\psi^-(o_p)\cap\psi^+(o_p)=\emptyset$ for $\exists$ $o_p \in O_P$ and $\psi\in\Psi$, then the mapping Ψ is called operating function or production function, for which tuples (Ψ^-, Ψ^+) represent the input and output function; $\Psi^-(Op)$ input object and $\Psi^+(O_p)$ output object; the tuple $G_p(O_p, \Psi)$ is called **production graph** and represents the ***production structure***.

The production graph is a directed graph and function Ψ describes the transformation between input resources and output resources as performed by the actors. The set of functions $\Psi^-(O_P)$ define which product objects are required as input factors and function $\Psi+(O_P)$ defines the output product objects. Input and output factors for manufacturing operations are therefore product objects. Graphically, the arrow directions illustrate which product objects are considered input and which as the output of a function. In addition to describing the relationship of the function, the most important part is that the relationship can be different functions, each representing a business logic, such as determining product and component amount required, required time or even functions that are used for calculating costs. This makes the production structure highly adaptable to different functional purposes. Furthermore, due to the nature of these functions, their values are determined dynamically to its input parameters and therefore are not restricted to linear functions but can, for example, include discrete functions.

Since the production graph is a graph, it has a graphical representation. We adhere to the graphical representation of hypergraphs and mappings of similar models, in which hypergraphs are illustrated as a combination of black dots (resources) and circles or ellipses (hyperedges) and mappings as arrows [7]. An example production graph can be seen in Figure 1.

In this chapter, we have modeled a holistic model for the entire production structure. Due to G_P being a graph consisting of objects O_P and connecting activities Ψ and because we follow SDL, using G_P means that there is an underlying service object-oriented perspective on production structures. However, to make use of the production graph, it requires additional transformations based on its application purpose.

3.3. OPERATIONS AND PRODUCTION GRAPH PROJECTIONS

For operations, management must address two major issues, requirements planning & scheduling (RPS) and resource capacity scheduling (RCS). During RPS, managers need to assess whether an order can be manufactured and delivered in time. Resource capacity scheduling assesses how to optimally schedule manufacturing equipment efficiently. In this chapter, we will show how production graphs can be applied to address both tasks by means of mathematical projections.

Both RPS and RCS require different perspectives on the production graph, where one focuses on subject resources R_{subj} and the latter on supplementary resources R_{sup}. Therefore, $R = R_{Subj} \cup R_{Sup}$. Since the *production structure* $G_P=[O_P, \Psi]$ and we know that O_P is a hypergraph with R as vertices, we require a projection $Proj_{Subj}$ that projects a new production graph $G_{P.Subj} = [O_{P.Subj}, \Psi]$, which consists of all subjective resources, while keeping the original graph structure (activities). Conversely, for RPS, we also require a projection $Proj_{Sup}$ to derive graph $G_{P.Sup}=[O_{P.Sup}, \Psi]$. In other words, the projection that is required is a homomorphism. The homomorphism is a mapping from one graph to another graph that maps adjacent objects from the source graph to adjacent objects of the target graph. This means that the structure of both graphs is the same, as illustrated by Figure 1.

For applying production graphs, different production graphs need to be projected while selecting different vertices and retaining its production structure. Therefore, to find a homomorphism that matches our application conditions, we require a homomorphism f. f reflects the selection criteria, which in our case can be choosing only the subset for all subjective resources.

Theorem 1**:** Homomorphism between production graphs $G_P=[O_P, \Psi]$ and projected production graphs $G_{P.Subj} = [O_{P.Subj}, \Psi]$ and $G_{P.Sup}=[O_{P.Sup}, \Psi]$ retain their production structure.

Proof**:** For $G=[O, \Psi]$, we search $f\colon G \rightarrow H{:}G \mapsto [O_f, \Psi_f]$, with $\{G=[O, \Psi] \mid o \in O, o_f \in O_f, \psi \in \Psi, \psi_f \in \Psi_f$ and $O_f \subseteq O, \Psi_f \subseteq \Psi\}$. $f(G)= [O_f, \Psi_f] \therefore f(G)=[f(O), f(\Psi)] \because o_f \in O_f$ and $O_f \subseteq O \therefore o_f \in O. \because \psi_f=\Psi_f$ and $\Psi_f \subseteq \Psi \therefore \psi_f \in \Psi$.

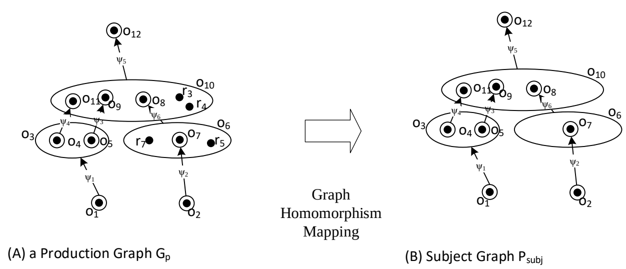

Figure 1 Graph Homomorphism

Before order production on the shop floor can begin, both marketing and production need a requirement plan, in which usually the bill of materials lists what parts or materials are required. In other words, they require a detailed list of subject resources R_{Subj}. All the required information, is also included in the base production graph G_P. However, in G_P both subject and supplementary resources are included, while the base structure tells what subpart or material is needed. Therefore, we make use of the above-mentioned homomorphism of a new target graph $G_{p.subj}$ that only includes the subject resources and retains the object structure. Based on $G_{p.subj}$, a detailed requirements plan can be derived. A type of input resources, coupled with the retained structure, which is in essence formalized as an induced graph, is needed to make a time schedule. The time schedule contains the information how long an order needs, which is often essential for marketing decision makers to reduce lead-time. Additionally, for a more accurate assessment of time-to-delivery, information of the capacity schedule is needed. Therefore, capacity scheduling ideally should happen simultaneously, if possible. Therefore, another induced graph $G_{P.Sup}$ with R_{Sup} as product object's element set is required. $G_{P.Sup}$ and $G_{p.sibj}$ are both homomorph and therefore the same in terms of structure, yet differ in terms of resources. For capacity scheduling, supplementary resources are required.

4. APPLICATION EXAMPLE

This chapter demonstrates the production structure's application potential by introducing how a production structure P_{Subj} can be transformed into a product structure and process flow model. However, its application is not limited to product structures and process flows. Depending on the chosen resources and especially the functional purpose, as defined by production functions, its application changes accordingly. However, we chose product models and their corresponding process flows for their central role in production [14,21,22,24,25]. Therefore, we specifically explore how functions are employed for different functional purposes, such as determining quantity, time or costs of the production (structure).

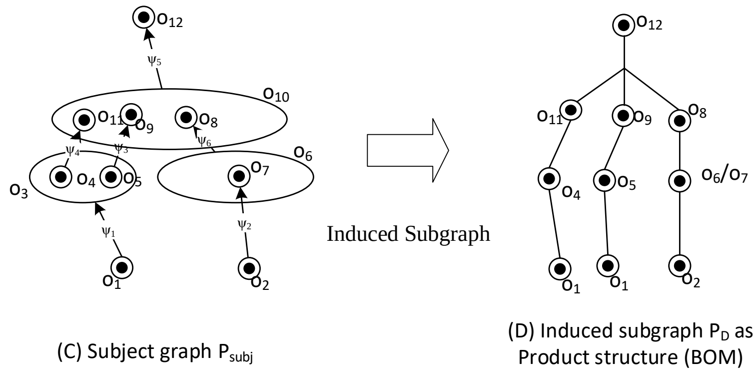

Figure 2 product model

Production graphs G_p are graphs that are based on hypergraphs and therefore are able to express a multitude of complex structures, which this paper is not able to cover. However, by choosing the above-mentioned subject graph P_{Subj} as an example, using mathematical operations, we can derive an induced subgraph that can represent a product structure. This induced subgraph takes on the form of a simple graph, as defined by [30], more precisely, it is a tree structure with the product as its root node. Therefore, consider P_{Subj} a production structure and homomorphism of production structure P_G, only consisting of subject resources, devoid of supplementary resources for purpose of this application example. Therefore, the original production structure G_P includes both subject and supplementary resources, such as materials and parts, as well as manufacturing equipment and utilities. The graph P_{Subj} includes all the input-output subject resources, relations and the necessary activities before a product O_{12} can be produced, including product variants. Since production relies heavily on product models, usually represented by BOMs [14], we transform the model into a tree, listing the products and its components (see Figure 2 D). Mathematically, the graph P_D is an induced subgraph of P_{Subj}, which sometimes requires additional mathematical operations, depending on the

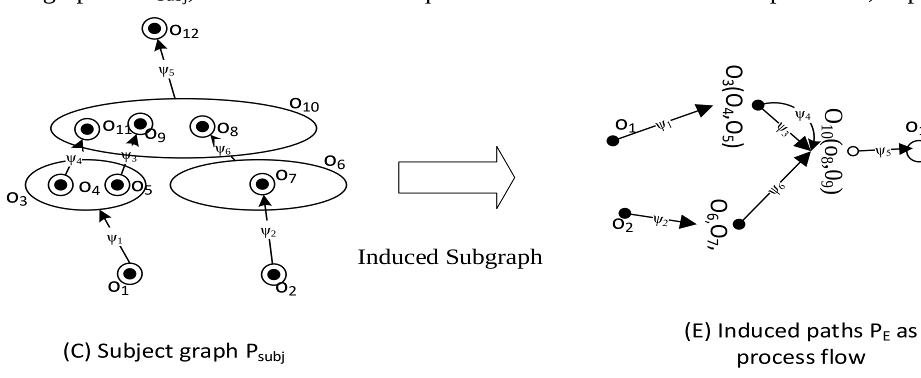

Figure 3 – Process Flow Model

graph structure, as Figure 2 shows. The graph P_D includes the necessary information required for a useful product model. However, there is a subtle difference at O_{11}, where some information has been lost. As Figure 2 shows, r_1 is not required as input for ψ_5, yet it is a byproduct of ψ_4. Therefore, P_D does not include r_1, since a BOM only includes the required materials and parts for a given product. Although this information is not relevant for product models, it shows the informational advantages of our production model towards conventional product models.

Product models are used in close conjunction with process models for different purposes, most notably for planning and scheduling [32]. Since our production model also includes information on production sequences, we can select the induced paths of P_{Subj} to model process flows, analogue to the induced subgraph for creating a product model. As Figure 3 illustrates, P_D shows how our production model includes alternative production paths, as illustrated by the simultaneous existence of ψ_3 and ψ_4.

After showing how a production graph can be used to derive conventional simple graph structures that are prevalent in production, we move on to touch upon the topic of functions. As shortly explained in chapter 3, activities are mappings between product objects. Its application potential lies in the chosen functions those mappings represent. As activities are transformational by nature [8], we did not specify precisely how they transform the subject resources of the input product objects. This is reliant on context. For example, to determine the lead time, at least the entire production time needs to be determined. This can be done by first determining the total quantity of products and components that need to be produced. This is achieved by analyzing a product structure, in our case P_D (see Figure 2). In $P_{D,}$ the activities represent the relationship of what elements are required and each function can determine the quantity of each required subject resource. After determining the specific quantity of each required part, the parameters can be taken as input for time-determining functions of a process flow model P_E (Figure 3). Since functions can be freely defined in software systems, a common production structure would therefore allow a combined function, determining both quantity and time simultaneously. Therefore, our production structure can be applied to different application scenarios. Quantity and time are just two examples. If quantity and time parameters can be determined, cost structures follow the same logic.

5. Discussion and Conclusion

Our production structure model is a step towards providing a unified model based on the service-dominant logic perspective that can be used for both services and production. We argue that our production structure model is compatible with service systems and can integrate both production and service activities into one structure. In this paper, we show that the production structure model can be used to induce both product models and process models, both being fundamental for production information systems.

Thus, our first contribution lies in the mathematical model of a novel production structure model using SDL as an underlying perspective. The production graph integrates a) an integrative model of both product structure and its input-output relations and b) a production structure model that introduces functions, so that input functions and output functions can be applied within a production structure's application system to calculate value. This was made possible by applying a service-dominant logic perspective and using the generalization of simple graphs into hypergraphs and its highly expressive power [30], which enables us to model more complex scenarios than conventional models that rely on simple graphs.

Our second main contribution lies in demonstrating the usefulness and versatility of our proposed production structure model. By exploiting the expressiveness of hypergraphs and applying the concept of homomorphisms and induced subgraphs, we demonstrate that the introduced production structure model is a viable alternative to both product models and process models. In other words, this paper a) introduced the production structure model and b) demonstrates that product models and process models are included in the introduced production structure.

For practice, in line with our research question, we explored a modeling approach for production that is compatible with service system graphs [7], yet addresses production. Future research should consider resource planning systems that are based on joint production graphs and service system graphs because such a system would have three main advantages to conventional production systems: 1) A mathematical model would simplify an application system's interface to databases, are a basis for simulations and can readily be modeled using conventional graph tools. 2) A production structure model that encompasses product and process structures enables innovative algorithms and heuristics for simultaneously planning for production time and requirements. 3) The hypergraph-based graph enables modeling previously hard to model complex production endeavors, such as chemical production and cyclical manufacturing. All three practical implications would require additional research. However, we call upon future researchers and practitioners to further explore the advantages of the production structure.

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