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A Tool-Independent Generalized Description for Sustainable Supply Chain Design

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Abstract

The purpose of supply chain design is to ensure an efficient and effective logistics network. Within supply chain design, simulation and optimization tools are used in combination to improve design scenarios from different angles. Nowadays, sustainability becomes an increasingly important criterion for the evaluation of these design scenarios. To integrate ecological and economical features, an exchange of results between an optimizer and a simulation model often improves the outcomes compared to one system only. Although the communication between both systems is frequently applied, it is also error-prone as the underlying models are tool-dependent and cannot be exchanged without any adaptations. The efficient use of the simulation and optimization tools requires a holistic data model depicting the elements of the network and their dependencies. Therefore, this paper introduces a tool-independent and generalized description of the supply chain. The significant advantage of this generalized description is its ability to exchange amendments between tools automatically.

Keywords: Supply chain design, modeling, optimization, sustainability, simulation

1. Introduction

The fundamental basis for the producing economy and a consuming society are energy and raw materials (Johansson 2002). Consequently, the competitiveness of manufacturing companies is always linked to the demand and availability of energy and raw materials. Companies are facing increasing economic challenges due to dwindling reserves of fossil fuels, rising global energy demand, and rising global demand for fossil and renewable resources. In recent years, companies' sustainability reporting shows a rapid growth (Lozano 2013), as ecological goals have been anchored increasingly in corporate strategies. Companies are not only concerned about how goods can be sourced sustainably, but also about the sustainability of their value-adding processes in production and logistics. Therefore, sustainability relates to the whole supply chain. In the supply chain management (SCM) task model, introduced by Kuhn and Hellingrath (2002), supply chain design (SCD) is a long term planning task. One major issue in SCD is taking sustainability into account (Longo 2012). In the past decade, research work has already been conducted in the field of ecological evaluation of production and logistics processes (Cirullies 2016). However, the results achieved in this context are only put into practice to a limited extent. The reasons are manifold.

On the one hand, there is a need for methods and tools, which support the evaluation and optimization

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of criteria measuring sustainability in production and logistics networks. Optimization methods alone are not always suitable as they can lead to a potentially vast number of design scenarios of the production and logistics network. Hence, the application of simulation as an interface for optimization has proven to be helpful when searching for an optimal solution (Rabe und Goldsman 2019). On the other hand, the relevant data for sustainability parameters are often missing or hard to collect. This typically results from the lacking availability of suitable methodologies, e.g., for standardized inclusion, calculation, and allocation of energy consumption at network and site level to ensure the comparability of energy indicators in the production network.

There is another impediment to integrate sustainability parameters in simulation and optimization efficiently: The use of different models. Relevant data of the production and logistics network needs to be maintained in all models, which results in an avoidable overhead and is error-prone when findings are transferred from tool to tool. A manageable, in particular, tool-independent, generalized description of the supply chain (SC) is necessary. This description requires convertibility into tool-dependent models and an exchange between tools without the need to maintain each of these models manually.

This paper introduces a generalized description of the SC to support the evaluation of sustainability criteria in SCD. This approach has been validated in the SC of one of the world's largest steel processing companies in the context of the E²Design (E²-Design 2020) research project funded by the German Ministry.

The paper is structured as follows: Section 2 underlines the importance of a combination of simulation and optimization tools in SCD and describes an approach on how to combine those. In section 3, a process is introduced to illustrate the creation of a generalized description that can generate models for simulation and optimization from one data source and store the results of several tools to create a continuous feedback loop. Section 4 provides a brief example of the generalized description in JavaScript Object Notation (JSON-file format). The paper closes with a summary of key insights and an outlook on further research.

2. Combination of Simulation and Optimization for Modelling of Sustainability

To take the sustainability aspects within the SCM into account, methodological approaches are required, which allow to evaluate key performance indicators (KPIs) for various elements of the SC and integrate them into the decision-making process. So far, ecological aspects in production and logistics have rarely been taken into account from a holistic perspective (BVL 2016). Continuous modeling of the network and production level of the supply chain is therefore required (Rabe und Goldsman 2019) and can be applied simultaneously by, e.g., simulation and optimization tools to achieve a sustainable network design.

The application purpose of simulation and optimization tools are generally twofold within SCD (Seidel 2008): Optimization can support individual design decisions in the SCD task (Parlings et al. 2013). This optimization comprises local optima for partner selection, facility selection, sourcing process design, and similar decisions (Schreiber 2019). Simulation, on the other hand, enables a holistic evaluation of specific scenarios compared by selected KPIs. Due to various design scenarios that result from optimization, a large part of the contribution of simulation results from the evaluation of the optimization (cf. Rabe und Goldsman 2019). Taking the energy performance of a site as an example, optimization tools can be used to create different system loads, each with its own sustainability profile. The energetic evaluation of these different load scenarios can be carried out using a simulation tool. To achieve defined goals of sustainable network design, the combination of simulation methodology and optimization is, therefore, indispensable.

Seidel (2008) identified the demand for a SCD process that allows rapid, efficient, and realistic modeling and evaluation. The elaborated integrated method of static scenario optimization and dynamic simulation is efficient and rapid. It provides KPIs of the granularity and abstraction levels requested in the course of the SCD-process. Schreiber (2019) introduces an approach for a holistic framework for sustainable SCD, including optimization and simulation, as it is used in the E²Design project (see Figure 1). The framework can be used to create a constant feedback loop between simulation and optimization tools. The objective of the framework is to optimize KPIs that have different weightings. In the first stage, analytical methods are used for this purpose.

This integrates analytical tools for supplier selection, network optimization for allocation and dimensioning of production plants and a flow optimization tool for determining lot sizes and bundling of flows of goods. The results of these analytical tools affect each other, though. Hence, with these tools, different initial scenarios are created and converted into models that can be applied in simulation. The simulation enables the evaluation and preparation of the scenarios from a holistic supply chain perspective. The results are used to adjust the KPIs and their weightings, thus creating a feedback loop. A generalized description for the SCD task is an essential deliverable in the E²Design project, and Schreiber's approach for a holistic framework is the first step towards this aim, which will be extended by this work.

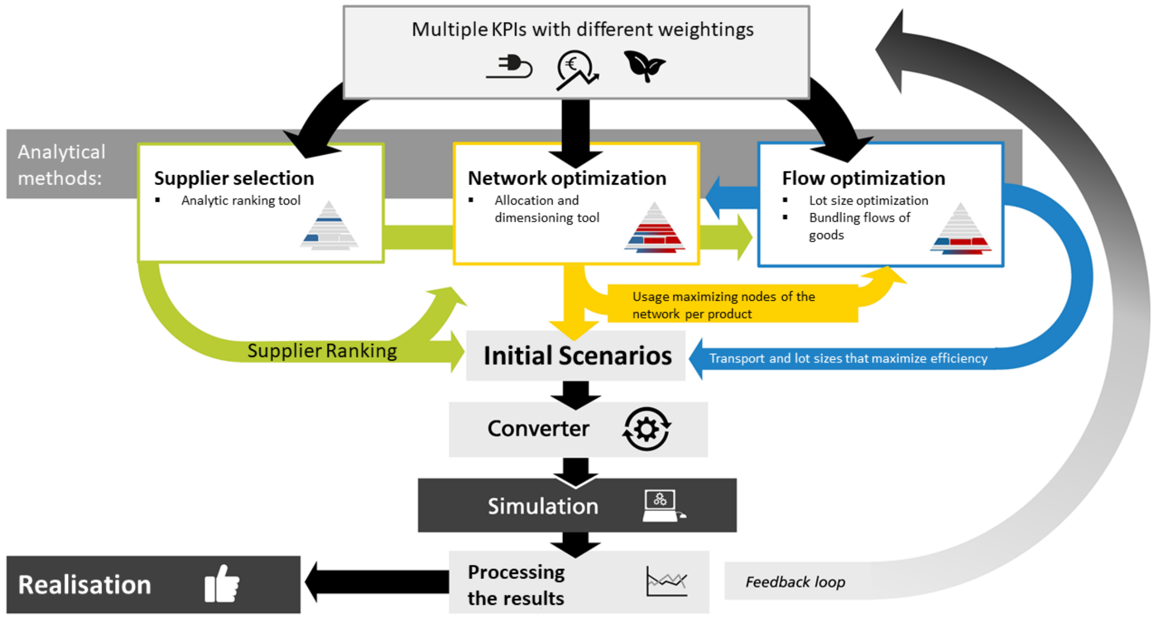

Figure 1. A holistic framework for orchestrating sustainable supply chain design (cf. Schreiber 2019)

As a sustainable network design requires continuous modeling, all models for optimization and simulation are subject to constant changes. Keeping those models up to date generates an overhead and is resulting in an error-prone process. Therefore, it is necessary to develop a tool-independent generalized description of the SC that can be used to generate models for simulation and optimization and thereby create a basis for a feedback loop between the tools. As a result, users will be able to use optimization tools to generate design scenarios for the SC combined with simulation for a holistic overview of those design scenarios, comparable by KPIs. Also, it addresses the possibility of transferring the tool-independent model between different simulation tools. This will lead to a fast construction of a generalized description and reduces the complexity of the simulation method at the same time.

The next chapter describes the development of a tool-independent generalized description and states its usage within the SCD process.

3. Generalized and Tool-Independent Description

Creating a tool-independent generalized description for sustainable SCs is a continuous process. As shown in Figure 2, the starting point of the process can either be the analysis of the real-world SC or the design of a greenfield SC, resulting in a generalized description of the logistics and production network and processes (see no. 1 of Figure 2). This generalized description has to contain all data required by the various tools to be used to optimize the SC. This data must be at a suitable level of abstraction. In case the SC analysis has already been performed, and several models exist that are already used in different tools, the tools have to be combined on an appropriate level of abstraction to a new generalized, tool-independent description. The research project "Supply Chain Design" (Parlings 2015) already describes the need and an approach on how to support the users' design task by using a domain-specific language (DSL). So-called macro modules inside the DSL are used to interrogate relevant logistical specifications to analyze a particular question.

A method for sustainable network design requires consistent modeling of network and site-level, including new KPIs. The conventional KPIs of SCM primarily focus on the dimensions of logistics costs and logistics performance, but sustainability is becoming increasingly crucial for quantifying corporate success (Schönborn et al. 2019). These KPIs must be integrated into the generalized description (see no. 2 of Figure 2). Cirullies et al. (2011) defined goals for the evaluation of logistical performance extended by the environmental parameters, including the key figures of resource consumption, energy consumption, and emissions. Rabe et al. (2019) have integrated ecological KPIs for transportation within a SC model.

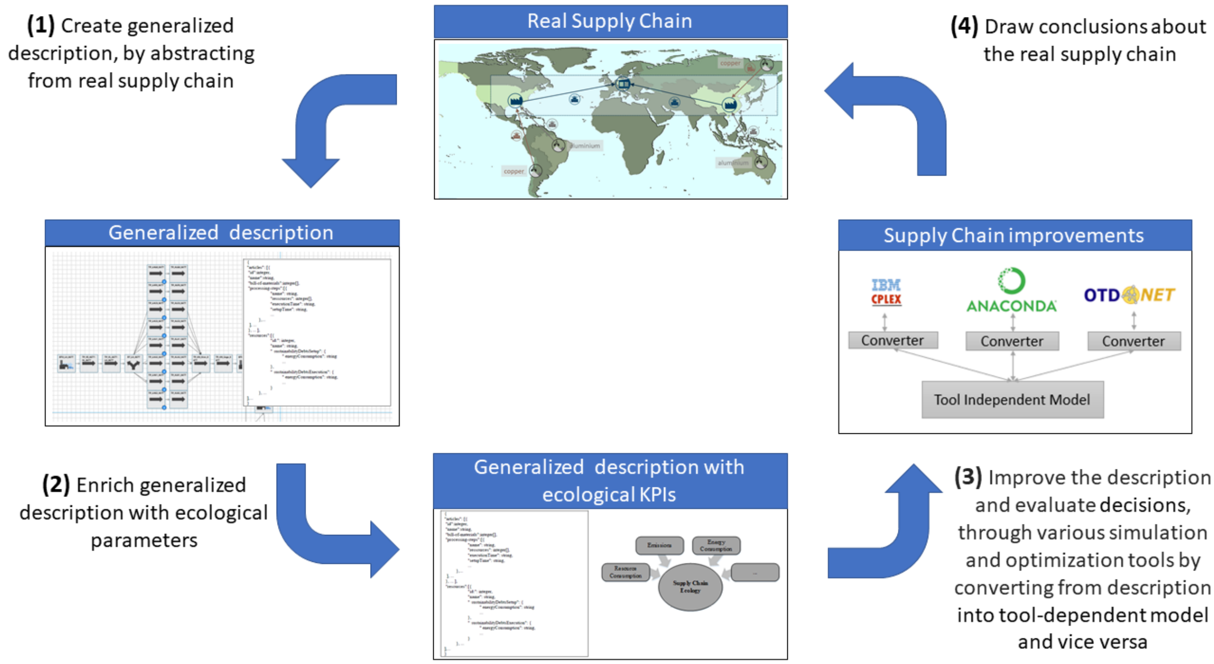

Figure 2. SCD process with a generalized description (based on Parlings 2015)

Furthermore, several frameworks and databases might be used to integrate new parameters. For example, the GLEC-Framework (Smart Fright Centre 2019), a calculation and reporting methodology of the logistic footprint, can be used to add ecological parameters into the generalized description. The GLEC-Framework is a good starting point to estimate the ecological footprint of the logistic as it uses average values and is used in the E²Design project in combination with other methods to integrated sustainability parameters. To refine the ecological parameters for road logistics, the HBEFA (HBEFA 2018) database can be used. HBEFA is a database for emission parameters for the most common types of vehicles, such as cars, light and heavy commercial vehicles, buses, coaches and motorcycles. HBEFA provides thereby emission data for CO2 and fuel consumption. Besides the KPIs for transportation sustainability, KPIs for the production of goods, need to be defined, e.g., energy consumption, as well as the ecological footprint of processed products. To estimate the ecological footprint of processed products, life cycle assessment databases like ecoinvent (Wernet et al. 2016), ProBas (Umweltbundesamt 2020), EPLCA (EPLCA 2016), or others can be used. Jamer et al. (2020) have proposed a model to integrate energy efficiency as a parameter for the strategic procurement of electronic parts and components. By knowing about the cumulative energy demand of material in a region and the exact material composition of a part using X-ray fluorescence spectroscopy, an energy value can be assigned to the part. Measuring the ecological parameters, e.g., energy consumption in production, seems to be a significant overhead at first. Still, if considered within the SCD, it can save substantial amounts of resources in the long run. The same applies to the ecological footprint of the delivered parts. In the long run, the declaration of the ecological footprint is considered to be a mandatory requirement of the product, as, e.g., the carbon labeling has recently received great attention (Khan und Lan 2019). In addition to the environmental and ecological parameters mentioned, the generalized description can be expanded to include many other sustainability parameters. To identify them, the GRI standard (GRI 2020) can be used. The modularly linked standard consists of three topics, which are congruent with the three-pillar model of sustainable corporate development (UN 2002).

Within the E²Design project, this generalized description will be translated into computable models for the OTD-NET Simulator (OTD-NET 2020) and for the optimization of customer allocation to a plant in IBM CPLEX (CPLEX 2020) to show that this approach works.

Figure 3 shows the result of such a computation in an application case where the material allocation and delivery areas within a distribution network have been optimized regarding energy consumption. The optimized SC footprint drives down consumption for processing, intersite and last-mile transport to customers. The overall site consumption for the site Nuremberg (green circle) decreases, e.g., from 770 GJ to 453 GJ. The energy consumption for the site Munich (blue circle) decreases from 659 GJ to 501 GJ. The lines show possible transport routes, which were included in the optimization process.

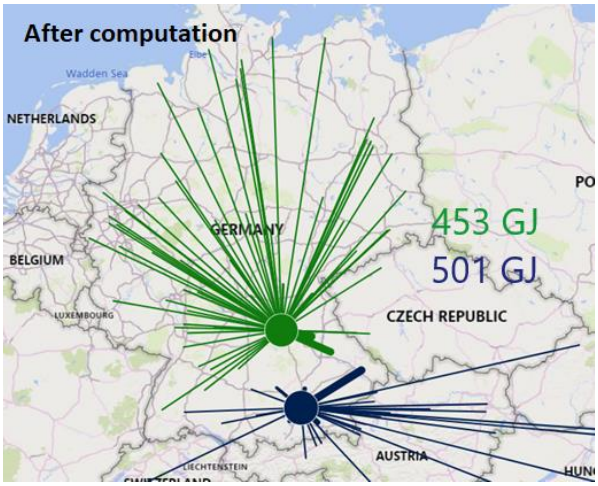

Figure 3. Resulting optimization from a use case of E²Design

The next steps are the implementation of additional converters for other simulation and optimization tools. This will allow the usage of standard tools to optimize the SC (no. 3 of Figure 2). In this way, the results from an optimization of the supplier selection can serve as input for the simulation - as intended by the holistic framework for orchestrating sustainable SCD by Schreiber (2019). Therefore, it is easier and less error-prone to draw conclusions about the real SC (no. 4 of Figure 2). Furthermore, with the use of converters and a tool-independent generalized description, it is easier to integrate new tools into the SCD process. The next chapter shows a brief example of a generalized description.

4. Generalized Description for a Production Process

In the context of the E²Design project, one of the use cases determines the energy balance of manufactured parts of one of the largest German steel manufacturers. Therein, parts are manufactured in a Build to Order process (BtO). These parts are either processed at the respective site or delivered from other locations via cross transports before they reach the customer. During the manufacturing process, different tools are used, including a crane and a metal saw, whose energy values are recorded. The BtO process has been designed using the Graphical Modelling Environment (GME) of the OTD-NET (see Figure 4).

For the presented process, a generalized, tool-independent description was developed in form of a JSON-schema to be able to convert the process and the related parameters into other models besides OTD-NET (see Figure 5). Figure 6 illustrates a brief JSON example using the schema. The JSON example describes a production process within the supply chain. There are articles with their bill of material (BOM) and production steps. Items that are delivered through suppliers have the attribute "sustainabilityDebts" In this context, sustainability debts represent the amount of, e.g., CO2, CO, NOx, energy consumption in Joule, or other sustainability parameters that arise during the production and transportation of an article. There are different ways to record these sustainability debts. In case a supplier cannot provide the sustainability parameters for its material, the parameters have to be calculated approximately using the various product life cycle assessment databases (see Section 3).

The individual resources also have been extended with sustainability parameters in the JSON-file. A distinction is made between setup time and execution time in sustainability debts. The production steps of an article refer to resources and specify a setup time and an execution time. With the specified sustainability debts of the resources, it can be calculated how high the sustainability debts of an article are. Therefore, it is necessary to iterate recursively over the BOM of an article and its process steps. For each process step, the setup and execution time needs to be multiplied with each parameter of the sustainability debts of the resource. Recursion is necessary because the BOM of an article can also contain articles with a BOM. The JSON-file shown in Figure 6 depicts the article "Round steel 20mm cut". It includes in its BOM the article with the Id 2 ("Round steel 20mm"). Further, the article includes the process steps "transport to working area cut steel", "transport to storage", which require the resources with the id 1 and 2 - metal saw and crane. For these resources, the energy demand during setup time and execution time can be determined to utilize energy measurements, to be able to determine the energy consumption of the machines approximately. Each process step has a "setupTime" and an "executionTime" with given duration. The sustainability debt for every process step can be calculated by using the duration of "setupTime" and "executionTime" and the sustainability debts during these phases. For the process step "cut steel" this would result in a sustainability debt for the parameter "energyConsumption" of 1 MJ/h * 0.43h + 1.8 MJ/h * 1.0h = 2.23 MJ.

To calculate the total sustainability debts for the article, all process steps would have to be taken into account as well as the sustainability debts of the articles in the BOM. This JSON-file is just a brief excerpt of how a general description is structured to map the supply chain and its sustainability parameters and make them available regardless of tools. Thus, the developed JSON-schema covers the supply chain in more detail, e.g., individual transport routes of articles can be traced. The developed JSON-scheme is tool-independent and therefore allows the usage in different methodologies. It will be used in a supplier selection optimization tool, a transport network optimization tool, a flow optimization tool, and a simulation tool, in the E²Design project.

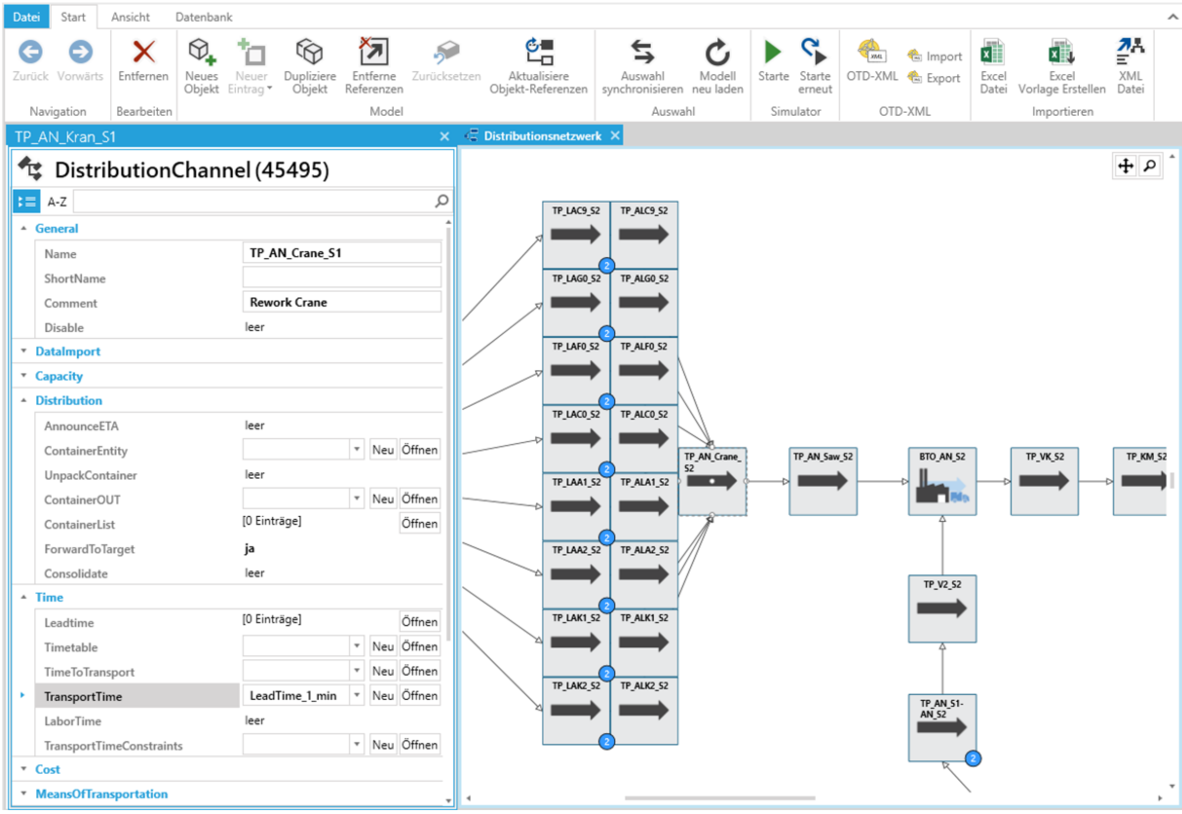

Figure 4. Process simulation using the GME of OTD-NET

```
{
"articles": [{
 "id":integer,
 "name":string,
 "bill-of-materials":integer[],
 "processing-steps":[{
                    "name": string,
                    "ressources": integer[],
                    "executionTime": string,
                    "setupTime": string,
                    …
          },…
  ], …
 }, … ],
 "resources":[{
                    "id:": integer,
                    "name": string,
                    " sustainabilityDebtsSetup": {
                              " energyConsumption": string
                              …
                    },
                    " sustainabilityDebtsExecution": {
                              " energyConsumption": string,
                              …
                    }
          }, …
],…
}
```

Figure 5. Excerpt of the JSON Schema

The main advantage is the abstract representation of the logistics network and its parameters, which is independent of tools and, therefore, can be created without any specialized knowledge of the tools. Thus, new tools can also be embedded faster in the feedback loop of optimization and simulation. The fact that the tools convert their results into an abstract representation means that the newly acquired knowledge can be incorporated into new calculations for other tools more quickly.

5. Conclusion and Outlook

For the SCD task, many tools exist, each with its own tool-dependent model. The need to improve the sustainability of the SC also causes a need for a tool-independent generalized description, to store information about the logistic and production network as well as sustainability parameters of the SC and will make this data accessible to all tools used in SCD phase and beyond. Therefore, reducing the effort to keep all models of all tools used in the SCD phase up to date. Furthermore, it enables the establishment of constant feedback-loops between the tools. A planner could maintain a tool-independent generalized description without specialized knowledge about simulation or optimization methodologies as it has a high level of abstraction.

This research is an important starting point as it introduces the need for a tool-independent data model to simulate and optimize sustainability in SCs, especially during the SCD phase, and presents a first idea on how such a tool-independent generalized description could be created. In the future, insights of this paper will be used for the development of a tool-independent generalized description, supporting the SCD process. The developed solution will be evaluated using a SC of one of the world's largest steel processing companies.


```
{
"articles": [{
 "id":1,
 "name":"Round steel 20mm cut",
 "bill-of-materials":[2],
 "processing-steps":[{
                    "name": "transport to the working area",
                    "ressources": [2],
                    "executionTime": "1.0h",
                    "setupTime": "0.03h",
                    ...
          },{
                    "name": "cut steel",
                    "resources": [1],
                    "executionTime": "1.0h",
                    "setupTime": "0.43h",
                    ...
          },{
                    "name":"transport to storage",
                    "resources":[2],
                    "executionTime": "1.0h",
                    "setupTime":"0.43h"
                    ...
          } ], ...
 }, {
          "id":2,
          "name": "Round steel 20mm",
          " sustainabilityDebts": {
                    "energyConsumption": "4.6 MJ",
             ...
          },...
 }, ... ],
"resources":[{
                    "id:": 1,
                    "name": "metal saw",
                    " sustainabilityDebtsSetup": {
                    " energyConsumption": "1 MJ/h",
                              ...
                    },
                    " sustainabilityDebtsExecution": {
                    " energyConsumption": "1.8 MJ/h",
                              ...
                    }
          },{
                    "id:": 2,
                    "name": "crane",
                    " sustainabilityDebtsSetup": {
                    " energyConsumption": "0.9 MJ/h",
                              ...
                    },
                    " sustainabilityDebtsExecution": {
                    " energyConsumption": "2.2 MJ/h",
                              ...
                    }
          },...
],... }
```


Figure 6. Example of a generalized SC description

Acknowledgments

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