Towards an Integrated Virtual Value Creation Chain in Sheet Metal Forming

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Abstract. OEMs are focusing more on manufacturing critical components whereas non-critical components are outsourced to suppliers. At supplier's side, production planning process is intervened between sales and production processes. Past experiences can be adapted to support production planning activities. Hence, it is crucial to identify knowledge from previously solved cases on demand and assimilate it. At the Information Systems Institute, various methodologies (e.g., similarity search in product and process data) are developed to support aforesaid knowledge intensive activities in sheet metal forming. However, these methodologies are used as stand-alone applications. Therefore, the current contribution introduces an integrated virtual value creation chain in sheet metal forming which utilizes previously developed methodologies. Also, these methodologies are elaborated as part of the integrated virtual value creation chain. The developed methodologies are heterogeneous and are coupled through a shared knowledge base.

Keywords: collision detection, cost calculation, knowledge reuse, sheet metal forming, similarity search.

1 Introduction

Sheet metal forming, comprising methods like stamping, blanking, (deep) drawing, and bending, is an important production method for several industries, especially automotive [1]. In accordance to the importance of sheet metal forming, metal forming machine tools have a share of around 20% of the total amount of produced machine tools in Germany [2]. Due to increased complexity of components and ongoing trend of OEMs to focus on core competencies, an increasing number of sheet metal components are outsourced to suppliers for design and production.

At any given time, a customer is catered by different suppliers and, likewise, a supplier offers product development and production capabilities to different customers. As a consequence, customer and supplier have an intricate relationship manifested in a plethora of complex and interdependent activities in the course of developing and producing complex metal forming parts. Before production, a supplier performs various production planning activities supported by sophisticated tools from information technology. These activities are knowledge intensive and

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time consuming, and can include cost calculation, design, and the application of methods and tools from virtual prototyping. To execute these activities, customer and supplier employ ‘request-offer-order’ processes as depicted in Fig. 1.

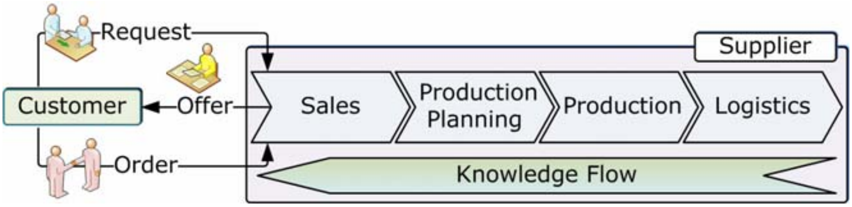

Fig. 1. Customer supplier interaction and value creation process at supplier

Production planning process is intervened between sales and production processes (s. Fig. 1) and collaborates with these processes to achieve production management goals [3]. Production planning process encompasses knowledge intensive and time consuming activities like process planning, scheduling and coordination of production processes. Hence for efficient execution of its activities, it should be equipped with knowledge about upstream and downstream processes. This knowledge can be assimilated to enhance value creation processes (e.g., resource configuration). Unfortunately, knowledge is not available for these processes as there are almost no efficient tools to identify it in the enormous amount of data generated during previously executed processes. In addition to knowledge, production planning activities should be supported with integrated virtual prototyping methodologies that optimize and ensure the required quality of value creation processes, in particular during production.

Due to these observations, the approach presented in this contribution aims at integrating knowledge-reuse by virtual prototyping methods. The remainder of this contribution is organized as follows. Section 2 elaborates an integrated virtual value creation chain in sheet metal forming. At each step of this value creation chain, knowledge can be identified on demand and applied, as elaborated from Section 3 to Section 6. Problem description, related work and methodology are elaborated for each process step. The contribution is concluded with a discussion on future work in Section 7.

2 Integrated Virtual Value Creation Chain

Customer-supplier interaction starts with a customer requesting information for capabilities provided by the supplier. The supplier should be able to respond to the customer’s request quickly with reliable information on time and cost utilizing information technology which supports knowledge intensive and time consuming activities. In this context, it is crucial to identify knowledge from previously solved cases on demand and assimilate it. These knowledge identification and assimilation activities at various stages in production planning are depicted in Fig. 2. The principle approach of each of these stages can be summarized as follows:

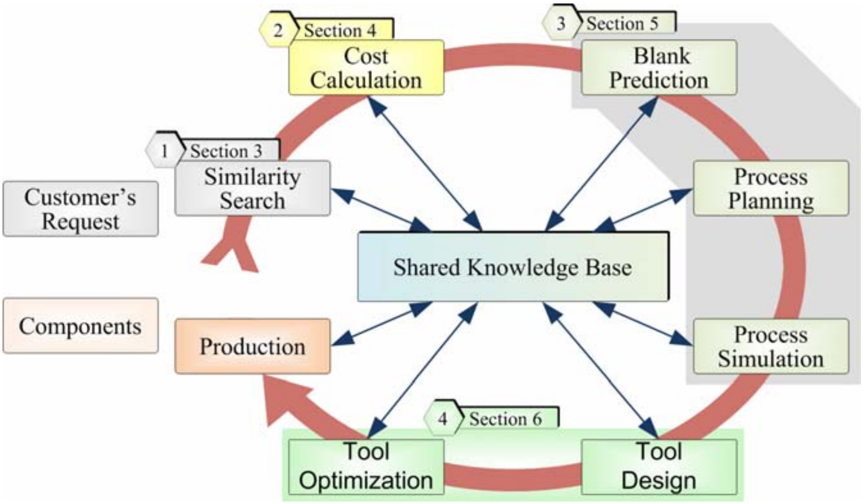

Fig. 2. Integrated virtual value creation chain in sheet metal forming

1. For a product requested by the customer, a similarity search system can be employed to search for similar products based on product's specification (e.g., material) stored in enterprise's product databases (e.g., Product Lifecycle Management (PLM) systems). The retrieved similar case and the associated product data (e.g., process plans) can then be utilized to enhance the production planning process [4] and also, act as a template which can be adapted by the domain experts to respond to customers' requests.
2. Manufacturing cost of a component includes tool-, material- and processing- cost. Information requested by the customer is derived using data gathered from different departments. This information should be sufficiently precise to increase the probability of getting an order and subsequently to avoid financial loss during order execution. However, manually obtaining data from different departments will delay the response to the customer. To speed up this task, a methodology has been developed which utilizes various systems (e.g., similarity search) and applies techniques from knowledge-based engineering (KBE) and case-based reasoning (CBR) [5].
3. Sheet metal forming process encompasses a sequence of metal forming operations like blanking, deep drawing, piercing, and so forth. Blanking is often the initial operation to provide a blank that can be further processed with the aforementioned metal forming operations. The prediction of an optimal blank shape (e.g., with minimal consumption of material) has already attained considerable attention in research [6]. The predicted blank shape is input for process planning to define the number and sequence of metal forming operations. Also, it will be used during cost calculation to estimate material utilization. Further, process planning is integrated with process simulation to ensure reliability of planned production process [7].
4. Based on a process plan, forming dies have to be designed and assembled using geometrical modeling process (i.e., CAD systems). Due to their complexity, sheet metal components have to be produced with multi-stage metal forming processes,

and subsequently, transportation of semi-finished components from one forming stage to the next has to be considered. As a consequence, collisions might occur between dynamic components (e.g., between transfer equipment and transfer dies). In addition, the configuration of transportation systems influences the achievable stroke rate of the forming press [8]. Hence, a methodology for collision analysis of metal forming processes using CATIA® V5 and a digital mock-up (DMU) software OpTiX® KINSIM has been developed [9]. The methodology is integrated with geometrical modeling of tool structure and aims at avoiding collisions during production as well as increasing the production performance in terms of achievable stroke rate. The stroke rate has to be (at least) equal to the value assumed during cost calculation process.

Each of the virtual prototyping methodologies mentioned above are utilized to address certain production planning activities, which are heterogeneous. However, these methodologies are coupled through a shared knowledge base. For instance, cost calculation utilizes similarity search to identify previous documents from a supplier's database, and blank prediction to determine the blank shape and material utilization.

After processing the integrated virtual value creation chain, the start of production is initiated. Executing the aforementioned virtual value creation chain mitigates production disturbances and increases production efficiency. The individual components of the virtual value creation chain are elaborated in the subsequent sections. The presented components (except for blank prediction) have been developed by the Information Systems Institute at the University of Siegen. For completeness, already existing tools for blank prediction, process planning and process simulation have been integrated into the outlined virtual value creation chain. Each section starts with a brief problem description, proceeds with presenting related work, and ends with elaboration of a methodology.

3 Similarity Search for Identifying and Reusing Knowledge on Demand

"In modern product development, as the complexity and variety of products increase to satisfy increasingly sophisticated customers, so does the need for knowledge and expertise for developing products" [10]. In addition, the necessity to shorten the time-to-market forces enterprises to accelerate and improve their product development by reusing knowledge. Knowledge related to development activities is tacit and embedded in the products. Products are described by product data (e.g., geometrical model, process data) which can be managed in enterprise's product databases (e.g., PLM systems). Enterprise members can access these product data and reuse it to shorten the time-to-market of new products. However, capabilities to efficiently search for various kinds of product data are not available.

3.1 Related Work on Similarity Search

Available search systems related to product data are mainly based on CBR. CBR can be explained as a cycle consisting of four steps [11]: First, RETRIEVE problem descriptions which are similar to a given (new) problem from a case base; second, REUSE the assigned similar solution; third, REVISE this solution, and finally, RETAIN the current problem and the new solution in the case base.

There are two approaches for assessing the similarity between products. First, assessing the similarity based on the products' geometries represented by means of 3D models [4]. A survey of possible methods and techniques to assess and retrieve similar 3D models is available in [12]. Second, assessing the similarity based on products' assembly sequences (e.g., bill of material (BOM)). A comprehensive overview of methods to determine differences between BOMs and measure their similarity is presented in [13]. Several retrieval systems and search engines have been developed for searching in enterprise databases. Most of these systems offer similarity metrics for numerical or alphanumerical data, and only a few of them are capable to search for products' 2D or 3D geometry [14, 15, 16]. However, there is no integrated search system which is capable to search for all of these different types of data simultaneously.

3.2 Methodology

A methodology has been developed to set up an integrated search system which is capable to incorporate similarity metrics for numerical, alphanumerical and geometrical product data [17]. This search system is based on CBR, and an architectural overview of the search system is illustrated in Fig. 3. The architecture consists of three main components: case base, retrieval system, and search views.

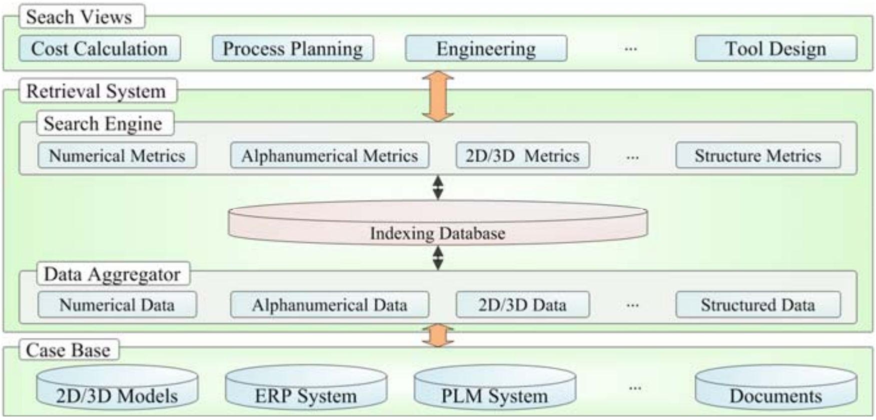

Fig. 3. Overview of search system architecture (adapted from [17])

In the context of product data, the case base consists of geometrical data (e.g., 2D/3D CAD models), bill of materials (BOM), cost calculations, process plans). Product-related documents along the product lifecycle (PLC) have to be analyzed to identify attributes that can be utilized to define similarity metrics. These attributes approximate the experts' idea of searching similar products, and are used to generate sufficient case descriptions. The case descriptions are managed in an indexing database and are linked to the cases in the case base. A data aggregator is in charge of deriving case descriptions to be stored or modified in the indexing database.

The core module of the retrieval system is a search engine encompassing various similarity metrics (s. “Retrieval System” in Fig 3). These similarity metrics combine techniques from different research areas to derive a similarity value. This value is used to retrieve cases from the case base. The search engine is capable of incorporating various data types (i.e., numerical, alphanumerical, and geometrical data) relevant in the context of PLC. View- and image- based methods are employed to measure the products’ visual similarity [18]. A density-based shape descriptor is utilized to evaluate the similarity based on local surface features [19]. To assess structural similarities (e.g., between BOMs), a graph-based distance measure is applied utilizing an extended Jaccard similarity coefficient. Edit-distance and Euclidean-distance metrics are used for comparing simple data types (e.g., strings). Different search views (s. “Search Views” in Fig. 3) are generated to grant enterprise members access to the retrieval system. The search views depend on the user’s profile and his privileges.

4 Cost Calculation for Quick and Precise Responses to Customers

Cost calculation is knowledge intensive and time consuming process, and the elaborated concepts and actual values depend upon a vast number of interdependent details within calculation, calculation depth, and the granularity of calculation. In many cases, a customer’s request will be waiting for processing, increasing the lead time to respond to customer’s request. Around 10% of the total offers are converted into orders [20]. Due to this reason, the cost calculation process is not performed in-depth in every case by domain experts from different departments. Instead, sales personnel often perform the cost calculation activities of domain experts. As a consequence, cost calculation will be based on sales personnel's limited knowledge and experience with the actual manufacturing technology. In addition, parameters used to derive the offer will act as inputs or constraints to downstream processes (e.g., process planning) and might cause problems during order execution. To overcome these problems and reduce unrealistic cost calculation, knowledge adopted by various departments has to be made available to sales personnel (s. knowledge flow in Fig. 1).

4.1 Related Work on Cost Calculation

The major components of an automotive body and chassis are complex sheet metal components and require metal forming operations to manufacture them [1]. Manufacturing cost of a component consists of tool-, material- and processing- cost [21, 22]. Cost calculation application is available with the sales department for metal forming processes [20]. Procedures to calculate amortization, processing costs, transportation and material utilization are embedded into this application and necessary information (e.g., material cost) is retrieved from databases. However, tool cost and forming press details should be provided as inputs which sales personnel is not in the position to determine these values preciously. In addition, tool cost depends upon the number of stages in a process plan and the actual metal forming operations performed at each stage. Research has been carried out in isolation to determine process plans in combination of feature-based engineering (FBE) and KBE [23, 24, 25], and sometimes using CBR [23, 26].

4.2 Methodology

To overcome aforementioned problems and support sales personnel with knowledge about downstream processes, a methodology to integrate various systems and techniques has been proposed as illustrated in Fig. 4 [5]. Information about enterprise resources, material and components along with previous offers/orders are stored in enterprise databases which form a case base (s. Fig. 3). A supplier will be collaborating with many customers and for a component in focus there is a high probability that a similar offer/order was created previously. Search system (s. Section 3) can be utilized to retrieve similar offers or orders and the result can be used as a template to create a new offer resulting in accelerated offer creation process and increasing reliability of the new offer.

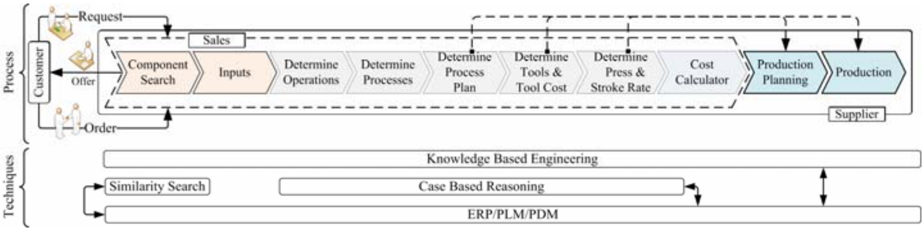

Fig. 4. Cost calculation process (adapted from [5])

Accuracy of the estimated values depends upon input data. Hence, data model of typical sheet metal forming features and operations can be hierarchically classified [23, 25, 27] and this classification can be further enhanced to include process plans and manufacturing resources. KBE is employed to capture individuals' expertise within an enterprise and manage it as rules. Rules are modeled based on the data model and assist sales personnel to validate inputs and determine unknown process parameters (e.g., operations). In many instances, design practices are based on past experiences and these experiences are adapted to solve new problems [26]. Knowledge and design experiences are stored in documents (e.g., 3D CAD models) which are part of the case base, and case base is enriched and enlarged with each step of the offer process. Rules are utilized to create an initial process plan which act as input to search the case base for old process plans and iteratively adapt the initial process plan resulting in an optimized process plan. This can be achieved using CBR technique, especially focussing RETRIEVE and REUSE steps. Once a process plan is determined and with assistance of rules, it is possible to calculate tool's size and cost, and select appropriate forming press and determine achievable stroke rate. The determined values can be provided as inputs to a cost calculation system [20] and subsequent production planning activities (s. Section 6).

The cost calculation methodology presented above is based on different techniques (e.g., KBE and CBR) and utilizes different systems (e.g., search system presented in Section 3) that support the reuse of existing knowledge. This can help to reduce mistakes in the early phases of PLC, and results in a quicker response to a customer's request comprising more precise information.

5 Blank Prediction, Process Planning and Process Simulation

For completeness, available third-party solutions for blank prediction, process planning and process simulation can be integrated into the virtual value creation chain. Process planning in sheet metal forming often starts with the determination of blank shape. A blank shape is an important input for calculation of material cost and has to ensure the feasibility of the forming process required to achieve the final shape. Research exists to provide methodologies for prediction of optimal blank shape [6, 28]. Further, commercial applications are available to optimize blank shapes [29].

Based on determined blank shape, further process planning activities are performed to derive the total number and sequence of metal forming operations. After design of every die face (metal forming operation) an incremental process simulation verifies the feasibility of the (partial) process plan [7]. Nowadays, commercial process simulation packages have been established in industry like Indeed® [30]. Problems (e.g., thinning of component) which would occur during production can be minimized or even eliminated before manufacturing the dies. Required corrections and redesign of blank shape and dies are done immediately, and subsequently, lead to smoother die try-out and shorter lead times [7].

6 Collision Detection and Optimization of Tool Structures

To realize production processes in sheet metal forming, progressive compound dies and transfer dies are used. In case of transfer dies, a peripheral transportation system (e.g., transfer system) has to be engaged to transport semi-finished components from one forming stage to the next. A tri-axis transfer system performs trajectories in three dimensions: in longitudinal direction to transport components, in transverse direction in the form of a closing movement for gripping parts and in vertical direction to lift out drawn parts [1].

A domain expert has to define the trajectories of the transportation system and forming press in the press control system. Collisions might occur during production due to inaccurate configuration of the transfer system and/or design faults in tool structures. Collisions are interferences between transfer equipment and transfer dies, but also between semi-finished components and the transfer dies. In addition, the transfer system configuration influences the achievable stroke rate of the forming press. Hence, main challenges during production planning are to design transfer dies and to configure the transfer system in order to avoid collisions and optimize the stroke rate.

6.1 Related Work on Collision Detection

Traditionally, collision curves are derived by the combination or overlay of motion curves (e.g., motion of opening/closing of the gripper rail). These collision curves are used to analyze if a critical point of the transfer equipment (e.g., gripper tip) is or will be in collision with other components during production [31]. The aforementioned approach is time consuming, and only includes a few parts of the geometrical model which are perceived by domain experts as critical. In addition, physical simulation is also carried out using manufactured transfer dies, transfer equipments and lower press [1]. Unfortunately, upper dies cannot be incorporated in such a collision analysis, and collisions detected after manufacturing of transfer dies result in costly elimination of errors [32].

Kinematics simulation has already been used to solve several engineering related problems. Extensive research has been carried out to simulate robots using different simulation tools and packages like MATLAB®, Open Dynamic Engine (ODE) and ADAMS™ (e.g., [33, 34, 35]). Also, validation of machining setup for selected NC machines can be done (e.g., using Tecnomatix RealNC [36]). Similarly to OpTiX® KINSIM, Tecnomatix Press Line Simulation enables the kinematics simulation of forming presses and handling devices [36]. Aforementioned approaches are expensive and non-optimal to detect collisions between transfer equipment and transfer dies.

6.2 Methodology

To overcome aforementioned drawbacks, a novel methodology for automatic collision analysis using DMU software OpTiX® KINSIM and CATIA® V5 has been developed [9]. An architectural overview of OpTiX® KINSIM is illustrated in Fig. 5. After analyzing various tri-axis transfer systems along with designed transfer dies, it can be deduced that the geometric shape of the dies and their assemblies varies whilst the trajectories of most dynamic components (e.g., grippers) are similar. Therefore, definition of kinematics mechanisms is separated from geometrical modeling of transfer dies by means of a kinematics reference model constructed in CATIA® V5.

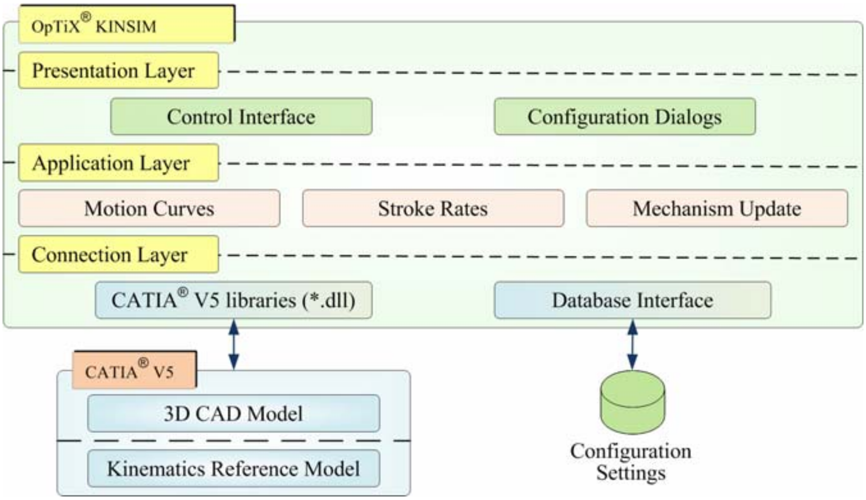

Fig. 5. Architecture of OpTiX® KINSIM and its interfaces to CATIA® V5 [9]

An interface between OpTiX® KINSIM and CATIA® V5 has been developed using CATIA® V5 APIs (connection layer). In the application layer, motion curves and corresponding stroke rates are calculated based on a given configuration of transfer equipment and forming press. This configuration is defined by a domain expert via presentation layer, and the resulting motion curves are transferred to the kinematics reference model using the mechanism update module (application layer). Configuration settings can be stored in a database which also contains vendor specific information about transfer systems and forming presses (e.g., accelerations).

After setting up the kinematics reference model within CATIA® V5, a collision analysis can be performed. As all dynamic components of tri-axis transfer are incorporated in the collision analysis, all collisions are detected automatically during simulation of production process. Although achieved results are adequate, the presented simulation approach could be improved by including dynamic effects (e.g., bending), which is now impossible with the standard functionality of CATIA® V5.

7 Conclusions and Future Work

In manufacturing scenarios, customers and vendors have an intrinsic relationship as well as interactions. At supplier's side, production planning is a critical process encompassing knowledge intensive and time consuming activities, and is intervened between sales and production processes. These activities have to be supported with knowledge to enhance value creation process. Information technology and virtual prototyping methodologies are required to identify and assimilate knowledge from previous experiences on demand. In addition, these methodologies need to be integrated to optimize and ensure required quality of value creation processes.

Current contribution has addressed the aforementioned requirements of production planning process. Integrated virtual value creation chain consisting of different methodologies has been elaborated from Section 3 to Section 6. Each of the methodologies supports different stages of production planning process by identifying knowledge on demand and assimilating it. Further, these methodologies interact with each other through shared knowledge base. Several methodologies of the outlined integrated virtual value creation chain have been put into practice by Co.Com Concurrent Computing GmbH, Siegen. The practical experiences gathered while using these methodologies can be utilized for further development activities.

In future, it is envisaged to enhance the available virtual prototyping methodologies and expand the integrated virtual value creation chain by including methodologies to support other stages (e.g., simulation-based feasibility study of forming components before process planning [7]) of the production planning process. Furthermore, research and development will also focus on the calculation of design space wherein engineers can design transfer dies without causing collisions during transportation and production.

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