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CONVERSION FROM TRADITIONAL MANUFACTURING TO DIGITAL MANUFACTURING, AN INDUSTRY 4.0 APPLICATION IN FURNITURE MAKING

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ABSTRACT

The concept of Industry 4.0 was presented to upgrade the manufacturing systems of large enterprises or even countries. Although some implementation paradigms and frameworks for implementation have been developed, only a minute selection suit the special needs and characteristics of small to medium enterprises (SME's). On the other hand, SME's account for a significant market share of the economy, and are in great needs to modernize and diversity their manufacturing capabilities in order to remain competitive in today's marketplace. In this paper, we present a framework for implementing Industry 4.0 in SME's. As a work in progress, the product customization and manufacturing sections of the aforementioned framework are being implemented, which are being utilized by a local furniture maker for a custom order of wooden bookcases.

Keywords: Industry 4.0, Digital Manufacturing

1. INTRODUCTION

The concept of Industry 4.0 was presented at 2011 by the German Industrial and Academic communities. The original purpose of Industry 4.0 is to implement manufacturing with higher degrees of automation, digitalization and intelligence. The concept is analogous to the introduction of steam engine during the first industry revolution at the end of the 18th century, electrical power in the second industrial revolution during the beginning of 20th century, and computer and IT technologies in the third revolution in the 1980's. Based on Cyber Physical System (CPS) and Internet of Things (IoT), Industry 4.0 aims to develop "smart factories" and "smart manufacturing" based on the technologies of connection and integration. The connection aspect includes linking and communication between manufacturing machinery, products, and physical along with the digital world. The integration aspect includes the "horizontal integration through value network, vertical integration of manufacturing system, and end to end integration through product lifecycle" [1, 2]. Similar concepts are smart manufacturing proposed by NIST, Factories of the Future, Industrial Internet

proposed by GE, Chinese Made in China, Society 5.0 of Japan, etc. [3].

Although multitudinous implementation paradigms for Industry 4.0 have been published, the majority are related to the scale of an entire country, or at least multinational enterprises (MNEs). Only a select few are about small and medium sized enterprises, which face different challenges and obstacles compared to larger companies. Mittal et. al discussed the SME and industry 4.0's roadmaps, maturity models, frameworks and readiness assessments, and stated "SME need to develop their own unique Industry 4.0 vision and roadmap" [4]. Frank et. al. discussed the implantation patterns in manufacturing companies and suggested that SME's need to focus on providing mass customization using flexible manufacturing technologies [5]. The internet and flexible digital manufacturing technologies in Industrial 4.0 enable the mass customization to all customers with reasonable cost and lead time.

Mass customization is one of the strategies that small enterprise can use to deal with the increasing competition along with imitation goods. It increases customer satisfaction and loyalty to specific brands. It also reduces cost of capital and cash flow variability. However, in the context of Industry 4.0 or Digitalized Manufacturing, the requirements for SME's to implement mass customization include:

- elaborate system for collecting customer information and requests that is capable of keeping customers involved while not having to divulge design and manufacturing details;
- highly modular manufacturing systems that are capable of being reconfigured to fulfill different small batch orders;
- strong Direct to Customer (D2C) logistics system that is capable of automating the processes involved in the flow of the products from ordering to delivery.

The same requirements exist in all Industry 4.0 systems but are more challenging for SME's. Regardless, it is possible to "scale down" and implement "customized" systems for specific SME's. In this study, we worked with a furniture maker at the Brooklyn Navy Yard convert from traditional build to order methodology, the order manufacturing, then lastly to digital

manufacturing of customized bookcases. We are developing a system called C2M system (customer to manufacturer) based on the roadmap of Industry 4.0, of which some of the recent work are presented in this paper. In Section 2, we present the traditional manufacturing process that is being utilized by most small furniture companies, along with the ideal process from collecting customer requirements to product delivery. This ideal process is developed based on the *modus operandi* of Industry 4.0. In Section 3, a detailed framework of C2M system is presented, which can be used for SME's and products beyond furniture. Section 4 introduces what was currently implemented in our project.

2. FURNITURE MANUFACTURING: TRADITIONAL, C2M, AND IDEAL PROCESSES

The traditional process, Figure 1, initializes when the customer visits a showroom of the manufacturer. The customer will be greeted by a salesperson who is usually also a furniture designer. After reviewing some sample furniture and printed catalogs, the customer, usually in the second visit, meets the salesperson/designer in order to create a model of their orders using CAD software. Most commonly, customers do not have the skill to operate CAD software and rely on the designer to help create the CAD model. Meanwhile, the designer takes notes of other information such as selected wood, color, hardware, etc. This step is time consuming and expensive due to the involvement of a designer, who can easily spend more than two hours on an order of a single piece of bookcase. Not only is this process expensive in regard to human capital, but it is largely inefficient as a result of the increased turnaround timeframe.

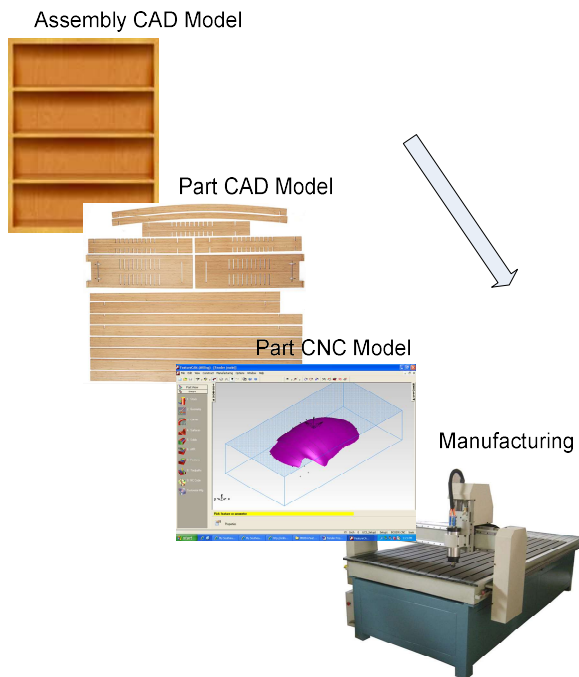


Figure 1. Traditional Furniture Ordering Process

Then, the order information, together with the CAD model of the bookcases, is emailed to the manufacture. An experienced employee, who understands the bookcase design, as well as the specific machining capabilities in the shop, “chops” the bookcase design, and rebuilds the CAD model of each piece from scratch. This includes, but not limited to, adding joints between wood pieces and recalculating the sizes of each piece considering the machining and assembly requirements. This step, yet again, is also very time consuming. Finally, an engineer generates CNC G-code for complex pieces especially the mortis and tenon joints. This code requires human reviews and modifications before being used on a CNC router as any mistake could be costly not only monetarily but also time-wise. After that, the following processes such as sanding, assembling, finishing, packaging and delivery, etc. are all carried out by workers and cannot be automated at this stage and budget.

The manufacturer plans to convert the current bookcase ordering and manufacturing processes to a digital system that enables customers to design bookcases online with a simplified and user-friendly software. The system must have two major functions the shop needs the most. a) The system should enable customers to design bookcases online without help from a furniture designer. b) The system should be capable of generating CNC G-code and shop instructions automatically. The instructions should be to give employees step by step guidance about the manufacturing process of each customized bookcase, such as the wood stock to be loaded, how to install work pieces on the router, dimensions of work pieces, joints types, filename of the CNC code, etc. This will greatly reduce human error and increase the flexibility of the entire process, hence allowing the manufacturer to customize products with much lower costs and reducing production time. The system is regarded as a C2M one, in which the steps from ordering to manufacturing are as follows:

- Customer reviews furniture samples at show room.
- *Customization*: Customer creates CAD model of the bookcase online.
- *Automation*: C2M system sends CAD model to manufacturer, and generates part models from the assembly model.
- *Automation*: C2M system generates 1) machine codes for machining the parts, or sections of the parts especially joints; 2) documentation including the material specifications, part dimensions, and step by step shop instructions.
- *Automation*: C2M system optimizes production control, such as inventory control, manufacturing resource planning, manufacturing execution system, input/output control, etc.
- Workers cut wood pieces using CNC wood router.
- Workers hand sand, assemble, finish, and deliver.
- Big data analysis enables customer to track delivery online, provide product improvement suggestions, and support system upgrade, etc.

Clearly the C2M system is not an ideal Industry 4.0 system, but an intermediate system that can be implemented by converting

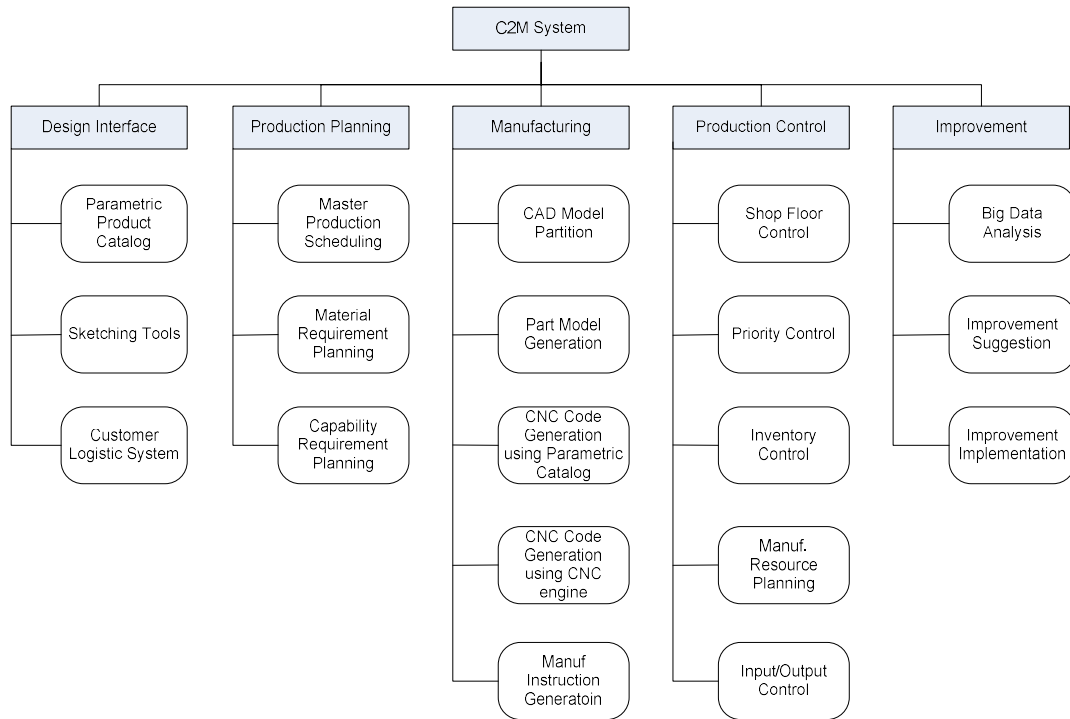


Figure 2. C2M System Components

from the current manufacturer's system. In a more ideal case, the process of such a furniture making SME will be:

- Customer reviews furniture samples from show room;
- Customer creates CAD model of the furniture online;
- Manufacturer follows instructions from the C2M system sequentially to complete the entire process, from loading CNC wood router with materials, sanding, assembling, finish, and delivery. All planned out after optimization;
- Customer traces and monitor the entire process of the order;
- C2M is constantly updated and improved with new data inputs harvested with collection algorithms to provide better customer service and experience.

3. C2M - CUSTOMER TO MANUFACTURER SYSTEM

System components of C2M are shown in Figure 2. C2M is developed considering its future expansion/adaptation to an ideal Industrial 4.0 system. Moreover, C2M can be used by any manufacturer, especially the ones making complex mechanical products such as small machines, appliances, etc. As a matter of fact, the system is designed with manufacturing mechanical products in mind. In the figure, C2M is composed of five major components.

Design interface allows customers to design their bookcase and monitor status of their orders. There are three modules. For lower level customization, bookcases with simple geometries can be represented using parametric CAD models. Customer can review product catalog and specify the parameters such as length, height, number of shelves, etc. Higher level customization requires customers to design their own bookcase using cloud

based CAD or sketching tools and upload the CAD model into the C2M system. This requires customers to be able to operate CAD tools. Besides, customers need to choose color, material, hardware, etc. However, the customer CAD software would rely more on simple graphical options rather than requiring the customer has advanced CAD and parametric design training. Not to mention, advanced CAD software often require strong and up-to-date hardware, which in turn would limit the customer pool. The third module is a customer logistics system that allows customers to submit orders and monitor their statuses until delivery [6].

Production Planning handles the logistics and planning activities related to manufacturing. This component is important if and when a relatively large batch of bookcases is ordered. Master Production Schedule (MPS) plans out when and how many of each part will be produced and delivered. The Material Requirement Planning (MRP) module ensures the appropriate materials such as wood, paint, etc. are available for each day of manufacturing, and sends reminders when stocks are low. The Capability Requirement Planning (CRP) aspect makes sure the equipment and labor resources are available for the master manufacturing schedule [7].

Manufacturing module deals with all the CAD/CAM related activities. One of the major tasks the furniture maker expects to be automated is the generation of CNC models and G-Code, which currently has to be carried out by experience employees and is very time consuming. In C2M, since bookcase models are created by customers, it is impossible to require that these models are created following the correct sequences from feature to parts and then to assembly. If different CAD software tools

are used, the part features may be lost in the process of file transformation. Moreover, for bookcases, CAD models must be re-created by adding the joints. Therefore, in C2M, the bookcase CAD model is first partitioned into blocks. Joints such as mortise/tenon are then added into the blocks, which are joined back into part models. This process can be accomplished automatically due to the simplicity of bookcases. The generated part models will be sent to the CNC toolpath generation tools, which generate G code based on the complexity of the part models. For simple parts such as straight boards with only joints added, we can create a database of parameterized G-code that can be easily regenerated using the parameter values from customized bookcase design. For a complex part that are unique from all other parts in the database, the part model are loaded into MasterCAM and can generate G-Code on the fly, which will require human operation. As introduced in the following section, we have developed parameterized G-code database for simple designs, which seems satisfied all the requirements of the furniture maker. Finally, the Manufacturing Instruction Generation (MIG) module generates a list of shop instructions that workers can follow when producing these parts on the CNC router. The instructions tell workers how to position the wood material on the fixture, how to fix the router head, which routing

bit will be used, and which G-code file should be run. All the information is stored in the G-code database.

Production Control manages the workshop and production related activities to make sure the necessary resources for the production plan are provided. Most of the tools are common in Enterprise Resource Planning [5] and Product Lifecycle Management System [8, 9], and can be integrated with the C2M system.

Improvement component automatically mines product data and conducts a big data analysis in order to continually improve the product quality and the manufacturing process. This is an important component of the C2M system, including the modules of Big Data Analysis, Improvement Suggestion and Improvement Implementation. In the era of Industry 4.0, the data from the entire lifecycle of the product will be greatly increased. The entire process of design, manufacturing, equipment with sensors and feedback, etc. is continuously generating large amount of data. The data should be used to support customers' involvement in the conception, development and manufacturing process. This will improve the manufacturing capability of the entire enterprise, eliminate the middle steps between customers and manufacturer, and improve the overall flexibility and capability of the company.

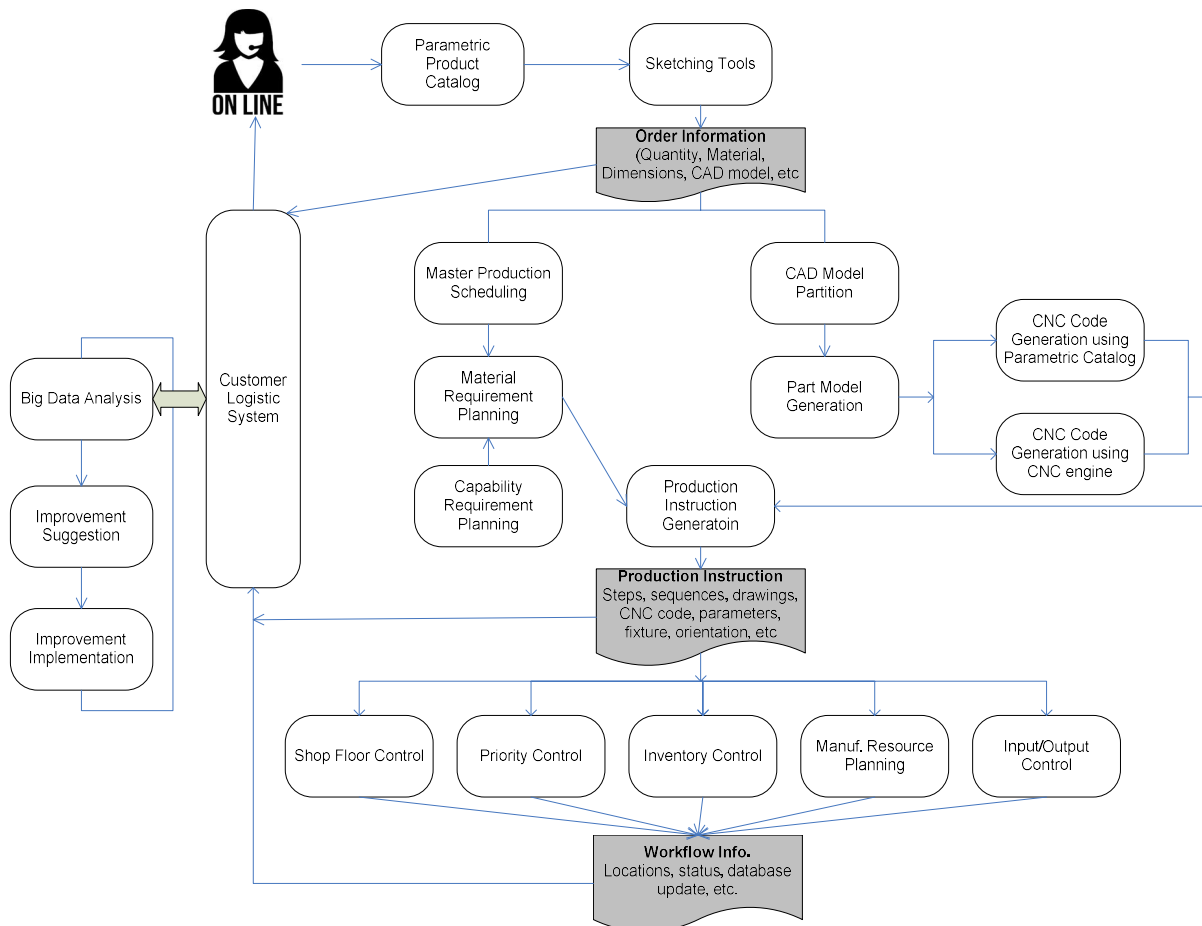


Figure 3. C2M System Architecture and Information Flow

The data includes information related to product design model, manufacturing, testing and maintenance. C2M analyzes collected data and achieves automation in this process. Customers can therefore focus on tasks related to mass customization. Data is also collected from business operation including but not limited to organization structure, business management, marketing, quality control, inventory, etc. The data will change how a business does research, development, product-ion, management and marketing. C2M also supports real time monitoring of equipment and machinery, as well as supply chain management. All these will contribute to reducing cost, increase efficiency, and optimize the planning of production. C2M aids in eliminating the intermediary vendors between customers and manufacturers, which can greatly increase the profit for the manufacturer. Moreover, manufacturer can understand customers' requirements in a more straightforward manner, hence making direct adjustments to its procurement, sales, customer service, etc..

The architecture of the C2M system is presented in Figure 3. It displays the relationship between these modules and information flow within the system. It can be seen that the Customer Logistics System (CLS) collects and analyzes all information from customers and the C2M system, and continually provides data for analysis and system improvement. Customers will operate the online parametric product catalog and sketching tools to design customized bookcase by specifying the values of the parameters and rendering a preliminary CAD model. Customer can then input requests into an Order Information data package. The package contains information about bookcase design, quantities, dimensions, materials, and colors, etc. This data package is passed to the other components in the C2M system.

Design related information is passed to the CAD model processing tools, in which the assembly model is partitioned and transformed into individual part models. The part models are again used to generate G-Code for the CNC router, through two separate paths exist for different levels of complexity, which has been discussed in Figure 2. Meanwhile, at the manufacturing path, all production related information including material, production capability, and master production scheduling are combined with the part CAD model to generate production instructions. The instruction covers each step of the

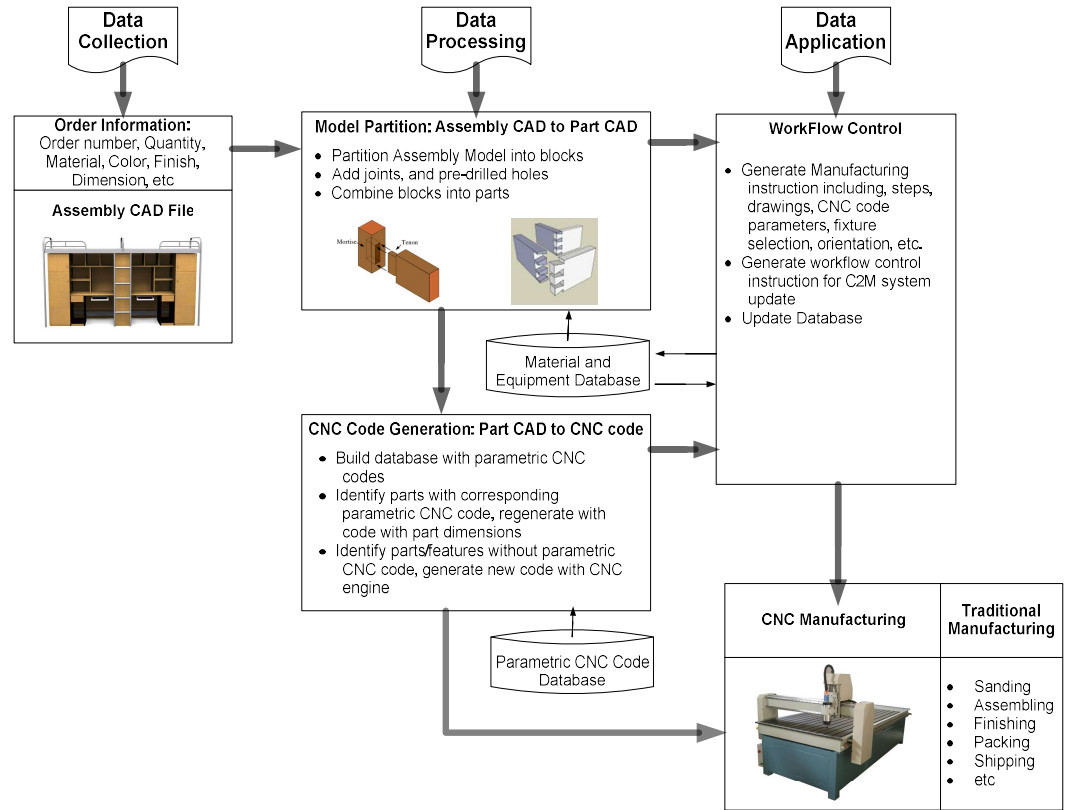


Figure 4. Implementation Architecture of C2M

manufacturing process, which will guide workers to select correct material, install the wood pieces on the CNC router on the specific fixture and location and orientation, and load the appropriate G-Code and run the router.

The production instruction package will be updated by the production control tools, which will collect information along the production process and compile them in a workflow information package. Together with product information and production instruction package, all the information is sent to the logistics system for analysis. Managers and supervisors will be able to review the results and decide the status of the current production, the history, and its predicated future. This will provide an all new perspectives to the manufacturer, which will make strategic decisions to aid in the competency of the business. Big data analysis will play the key role in the entire C2M system, thus is considered key technology in C2M.

4. IMPLEMENTATION FRAMEWORK

The C2M framework that has been implemented so far is a “scaled down” version of that presented in Figure 3. The furniture maker is a small shop that does not have any needs for manufacturing process optimization or workflow control. As shown in Figure 4, most of the works are focused on the manufacturing module of the C2M.

At the data collection stage, we developed an online spreadsheet using google sheet. The customer reviews the scanned catalog and fill in number of each parameter. A set of

parametric Inventor models were pre-created to cover all the possible design layouts, such as different number of shelves, with/without doors, different height, width and length, etc. It also has an identifying system to locate and regenerate the correct CAD models using the customers' input parameters. These model configurations offer a micro-level adjustment that can be modified by the customer parameters, while maintaining universality of designs that will ultimately decrease the necessity to maintain a large variety of inventory and tooling.

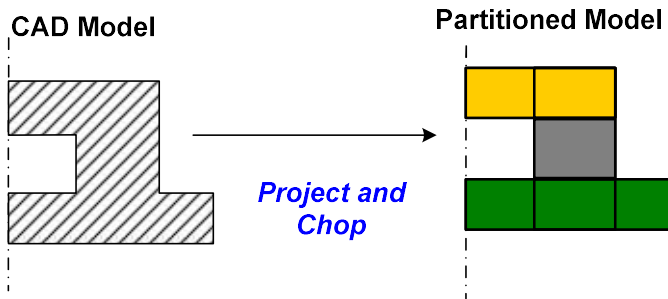


Figure 5. Bookcase Model Partition

The data processing stage includes bookcase model partition, part model generation and CNC toolpath generation. Due to the simplicity of bookcase, these are also implemented using parametric models. In general, bookcase model is partitioned using the method of “project and chop”, as shown in Figure 5. Detailed CAD model partition method is presented in [10]. The CAD model is chopped into definitive blocks composed of simple geometries. After adding pre-defined joints, these blocks are re-combined, or merged, into individual parts. This step is supported by a database of pre-defined parametric models, and available materials, equipment, machinery. Customer’s selection of certain type of bookcase, 2 top door & 5 shelf for instance, will decide which set of the parametric part models is used to generate the new part models. CNC code generation is completed using a set of pre-defined parametric G-code that is already available to the manufacturer. The G-code is mainly used to cut the re-defined joints on CNC router, Figure 6. The code can be easily re-generated by changing the parameter values which are decided by the part models. MasterCAM is used to regenerate CNC code on the fly when unique parts are needed, and still needs the approval of supervisor in the shop before running.

The last stage is data application, in which workflow control generates an instruction sheet for machine operators. These are simply instructions detailing to the technician how to complete the process. During the process, the material and machine database will be updated to reflect actual amount after the new manufacturing activity. Once the number is less than a preset limit, warning message will show up on the screen reminding it is time to restock materials. As stated in preceding sections, feedback systems are of utmost importance to the C2M system.

After these steps, the furniture was built following the same traditional process because most of these activities such as sanding and painting are labor intensive and could not be

replaced by automated systems under the allowable operating budget.



Figure 6. Wood Pieces on CNC Router

5. SUMMARY

In this paper, we introduced the project we are working on by collaborating with a local furniture maker. The concept of C2M is presented, predominantly a roadmap developed based on the idea of Industry 4.0. The current implementation is only a very small section of the entire system. Notwithstanding, the aforementioned portion is the most critical to SME’s.

The technologies still needed for the fully development of C2M is presented in Table 1. It shows the functions that are needed to provide mass customization to customers, and the technologies needed to implement the functions. It can be seen that although Industry 4.0 is being developed for large enterprise, most SME’s still lacks the basic automations. One solution is to develop an Industrial 4.0 system like C2M, that can be easily scale up and down as needed, and is being adapted to the specific product design and manufacturing process of each specific SME.

Table 1. Technologies Needed in C2M

Process	Customization Options	Enabling Technologies
Design	Component choice: size, style, material. Component design: shape, layout	Web based CAD Cloud computing
Production Planning	Production optimization	Production control software
Manufacturing	High quality parts, joints, reduced time/waste	CNC, robots
Distribution	Supply chain optimization	Supply chain management software
Post Purchase	Customer adjustment, customer service	E-record of every product, big data analysis, etc.

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