

INTRODUCING A ROAD-MAP TO IMPLEMENT THE UNIVERSAL MANUFACTURING PLATFORM USING THE METHODOLOGY OF AXIOMATIC DESIGN

Mahmoud Houshmand
Hoshmand@sharif.edu

Industrial Engineering Department, Sharif University
of Technology, Azadi Ave., Po.Box: 11155-9414,
Tehran, IRAN

Alireza Mokhtar
Mokhtar@mehr.sharif.edu

Industrial Engineering Department, Sharif University
of Technology, Azadi Ave., Po.Box: 11155-9414,
Tehran, IRAN

ABSTRACT

In competitive environment of quick market changes, developing an interoperable manufacturing system is a necessity. To realize interoperability, the exchange of part and product data must be independent of their platforms. There are two basic approaches for this purpose: i) Utilizing interface and ii) Utilizing neutral formats. STEP (Standard for the Exchange of Product data) plays a significant role as a neutral data model to integrate design and manufacturing and other activities in an enterprise. To implement a universal manufacturing platform, a systematic roadmap is required. The current paper proposes such a roadmap using the methodology of axiomatic design (AD).

Keywords: STEP-NC, Interoperability, Axiomatic Design, Universal Platform

1 INTRODUCTION

An economical firm needs to be quickly responsive and flexible to survive in today's competitive markets. For this purpose, the information related to the activities such as design, manufacturing, production etc. pertaining to the parts and products must be easily and rapidly exchangeable among the different computer systems. This exchange may also happen between the vendors providing different applications and protocols. In such a huge data transformation, information losses and misinterpretations between the departments and facilities would be unavoidable [Xu, 2005]. The solution to tackle this problem has been nicely introduced since a decade ago. Product data may be exchanged by employing STEP international standard, introduced in 1994 (ISO 10303). It stands for the Standard for Exchange of Product model. Using EXPRESS, a neutral and universal language, all the information generated in a product life cycle could be represented, maintained and easily manipulated to support the integration [Procter & Kramer, 1998], [Suh at al., 2003]. For example in the environment of Computer-aided design, manufacturing and process planning (CAD/CAM/CAPP), representation of part features may not be identical and different post-processors may be required to convert their information to be compatible for the variety of machine tools. Avoiding post-processing, STEP-NC as an

extension of STEP standard is able to provide a uniform data model and entail an accurately exchangeable format [Xu & Newman, 2006].

Considering manufacturing resources and environments, Newman and Nassehi has recently proposed an architecture for a platform which realizes the interoperability [Newman & Nassehi, 2007]. They name it "Universal Manufacturing Platform" (UMP). Although introduction to this platform is a big step toward the integration, it still need to be developed to encompass the entire production activities in a practical point of view. In each module, application and device layers also need to be separately postulated. In the current research, we first describe the need for data integration in manufacturing environment. Secondly, UMP and its impediments as a solution for the entire production echelon would be described. Then, we use one of the systematic design methodologies, so called Axiomatic Design to generate a roadmap for implementing the revised UMP. The proposed UMP includes all the production echelons such as manufacturing, manufacturing supports systems, production control. The main focus in this work is on the first echelon which deals with CAD/CAM/CAPP/CNC modules. STEP standard along with its extension protocols will be utilized to generate the roadmap.

1.1 NEED FOR INTEGRATION IN MANUFACTURING ENVIRONMENT

The product life cycle includes all the activities required to deliver the product to the market. This life cycle includes design, manufacturing, inspection, maintenance and disposal. The information generated about a product during these processes is used for many purposes. The enterprise integration approach originates from the need to control and integrate different functions in an enterprise [Gao et al, 2003]. The aim of enterprise integration is to standardize the way to designate its diverse aspects, for example the life-cycle phases and different views of the enterprise [Vernadat, 1996]. On the other hand, each of the aforementioned activities in product life cycle may be accomplished in a different enterprise throughout the product supply chain [Giachetti, 2004], [Jardim, 2006]. Therefore, the exchange of information must be facilitated so that each party in the chain would be able to seamlessly communicate with its corresponding parties [White et al., 2005]. Figure 1 shows how data exchange may be

performed between different manufacturing modules in the product supply chain.

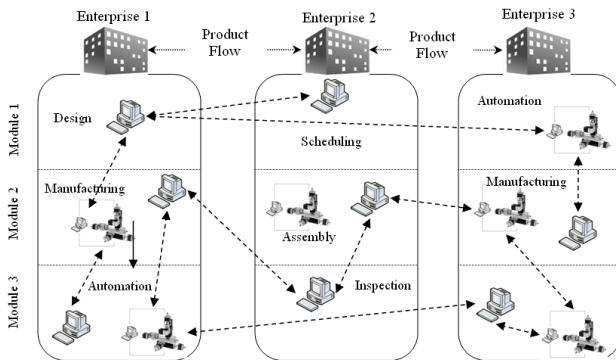


Figure1 Data communication in different modules from the different enterprises

Each manufacturing enterprise may consist of a mixture of diverse echelons such as marketing, production, finance etc. In production echelon, there are three main levels including Manufacturing, Manufacturing supports and Production control each of which can be classified into some modules (Figure 2). Since, in the current research the main focus is on the first level of production echelon, data exchange in its consisting modules, CAD/CAM/CAPP/CNC, is described in the following section.

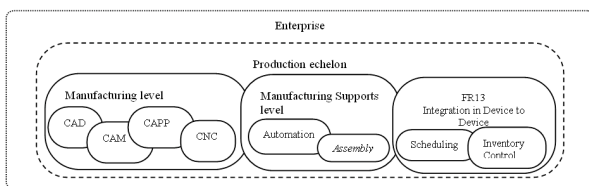


Figure2. Production echelon and its levels

1.2 DATA EXCHANGE IN CAX CHAIN

Manufacturing is one of the significant modules in the production echelon of a product life cycle. CAX chain (CAD/CAM/CAPP/CNC), associate with the part design, process planning and manufacturing tasks. Data integration among heterogeneous CAX systems has been widely researched [Fuh et al., 1996], [Patil & Pande, 2002], [Xu et al., 2005], [Alvares et al., 2008]. However, it has been universally accepted that using CAD data model cannot meet the requirements to realize the CAD/CAM integration [Sharma & Gao]. For instance, although machining features are the most appropriate representations of part information [Mantyla et al. 1995], when two different vendors provide CAD and CAM, features data and parameters cannot be shared because they utilize different standards. On the other hand, CAD and CAM modules from the same vendors may have confliction since design features are not the same as necessarily manufacturing features [Miao et al., 2002]. One approach to overcome such shortcoming is to utilize a neutral format to exchange the product data [Owen & Bloor 1987], [Qiao et al. 1993], [Bhandarkar & Nagi, 2000], [Oakham, 2003]. Some of

these formats includes STEP, IGES, PARASOLID, STL, SET and VDA, ACIS, Pro/E [Zhanga,], [Li & Kota, 2001]. Among all the neutral formats, STEP standard and its protocols found much more attention by the researchers and practitioners [Bhandarkar et al., 2000]. Unlike the other formats, STEP is able to specify the entire product data throughout the lifecycle, independent of any particular device or application [Xu & He, 2004]. To exchange CAX data including features information, design, process planning and manufacturing, STEP has been addressed by many authors. To extract the information of features, STEP data model has been employed [Bhandarkar & Nagi, 2000], [Dereli & Filiz, 2002], [Lau et al., 2005], [Holland et al., 2002]. In Computer-aided design, AP203 provide all the information to represent the part design specifications [Liu Zhang & Newman, 2006]. In developing a STEP-based process plan, AP 224 which encompasses mechanical features definitions, has been used [Sharma & Gao, 2003], [Amaitik & Kilic, 2005], [Qiao et al., 1993]. In other activities like inspection and process control, STEP has also found some applications [Ali & Newman, 2005], [Brecher & Vittr, 2006]. The majority of these researches consider prismatic features and components and reasonably deals with milling operations. However, in turning processes and rotational parts, STEP standard has been utilized [Rosso, Newman, Rahimifard, 2004]. STEP AP 238 and ISO 14649, recognized informally as STEP-NC has been extensively taken into consideration by researchers in order to integrate data in CAD/CAM/CNC environment [Hardwick & Loffredo, 2006], [Wang et al., 2005], [LEE, BANG, 2006], [Xu et al, 2006]. It provides a detailed and structured data model associating with feature-based programming and consist the required information for tools definition, machining technology and operations sequence [Xu & Newman, 2006]. Currently, STEP-NC does not generate tool path and this task is to be done by intelligent controllers (ISO 14649). Nonetheless, several attempts have been made to use STEP data to generate tool trajectory information for CNC machine [Suh et al., 2003]. In the following, the universal manufacturing platform proposed by Newman and Nassehi is discussed (Figure 3).

A platform generally consist of a software and hardware standard that supports a variety of applications by enabling them to exchange information through a communication system without knowing the particulars of the destination application. In such platform, information system must be so that manufacturing resources and activities are easily communicated with each other [Iwata, 1997]. Therefore, standardization in data transferring is unavoidable [Zimmerman et al, 2002].

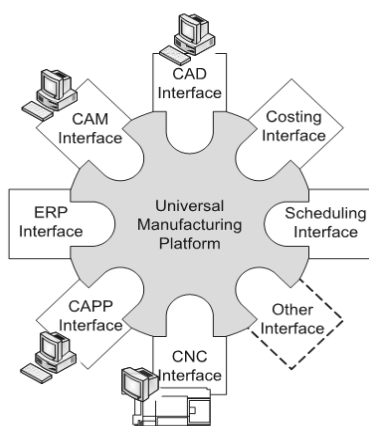


Figure3. Universal platform proposed by Newman and Nassehi

2 DATA EXCHANGE IN APPLICATION AND DEVICE LAYERS

In production echelon, at each level, two technical layers might be considered: application and device. Generally speaking, application and device layers deal with software and hardware for each of CAD/CAM/CAPP, etc. To realize the interoperability two approaches can be considered: (i) data interface and (ii) data exchange. In the former approach, an interface is designed and implemented to convert the input data from the source application/device into the desired format for the target application/format. Referring to Figure 1, when two CAD modules (e.g. from different enterprise) communicate their design specifications related to an identical part and they use different software application, data exchange would become an intriguing issue. To resolve this problem, two general solutions may be considered: (i) using an interface between two softwares so that each of them can read and write from and to it and (ii) using a neutral format plug-in to the softwares at both sides to easily exchange the part or product data. On the other side, depending on the kind of data communication (especially in e-manufacturing), a CAM file may be directly submit from a computer postprocessor to a CNC machine in the other enterprise. Likewise, both sides should have capability of read and manipulate data in a bidirectional data flow. However, most of the time, the postprocessor may be designed from a different company of that of the machine controller. For this purpose, the proposed approaches are: (i) using a soft/hard interface compatible with both device and application and (ii) using an intelligent controller in device side and a neutral format in application side. These approaches are depicted in Figure 6 and 7.

Using a device/device and device/application interface has been successfully experience by some of the Japanese companies like Denso, Toyota, Mitsubishi, etc. The solution was a software development kit called “ORiN2”. It provides two standardized software interfaces, Application Interface and Device Interface. It also can be extended by the add-in modules such as an application gateway and a provider. The main purpose to employ such an interface was to provide a unified access from a PC to a lot of devices such as an industrial robot and a PLC. (Figure 4)

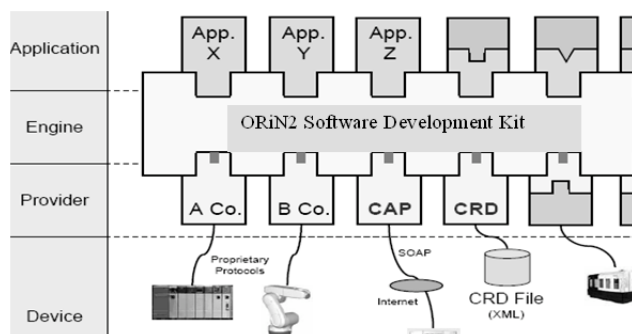


Figure4. ORiN general architecture

In the architecture proposed by Newman and Nassehi, as shown in Figure 3, CAD/CAM systems exchange information using their interfaces such as CAD Application or CAM application interfaces.

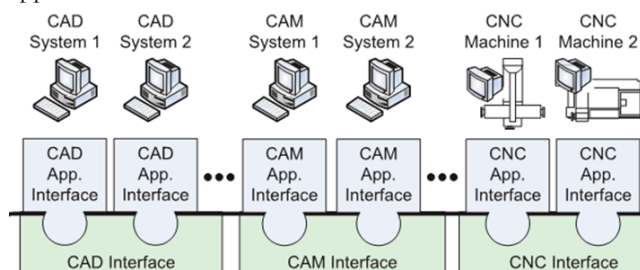


Figure5. Application interface in UMP architecture

In the proposed platform by Newman and Nassehi different interfaces have been postulated in order to make interoperability between the modules. Consequently, Figure 6, 7 display schematics of different possible communications between device controllers and application programs. Data communication between two programs could be possible using whether a neutral data format or an interface program. This become practical when for example a CAD software is able to export the design file into STEP file and the other program (e.g. CAM software) import it as a STEP file. Otherwise an interface must interfere to read and write both specific formats from the two softwares. Such an interface is shown in this figure5, as Application/Application interface. Two different device (like a CNC and Robot) can communicate in the same ways. However to use an autonomous format like STEP, their controllers are better to be fully compliant with STEP standard.

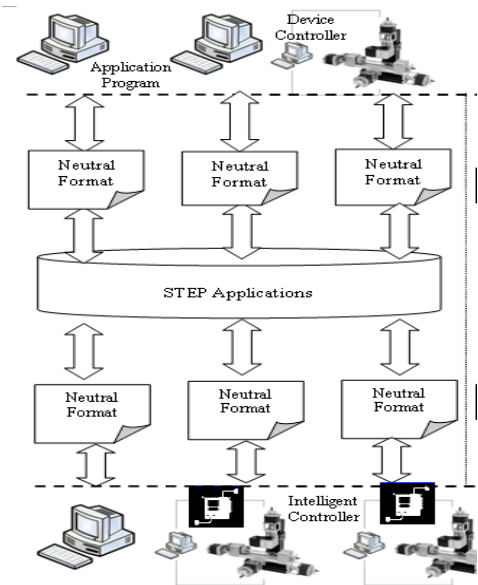


Figure6. Solutions A for interoperable data communication

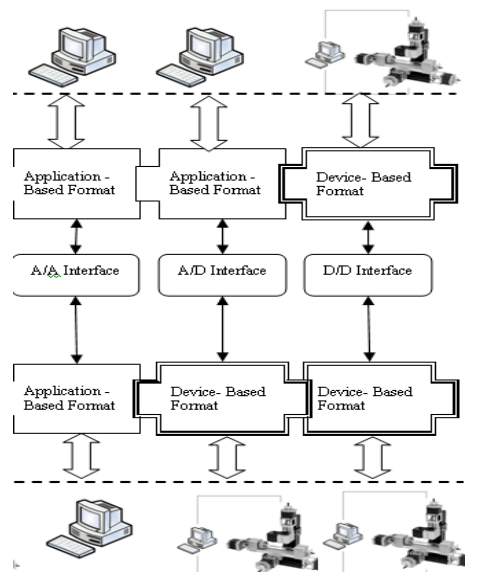


Figure7. Solutions B for interoperable data communication

In production echelon, these kinds of communications between device controllers and application programs are frequently happened. Alongside of numerous advantages of developing a universal platform to realize interoperability among device and applications, one of the most challenging issues is intelligent controllers. Original equipment manufacturers can reduce the time they spend preparing data for their suppliers by as much as 75 percent if they can seamlessly share the design and manufacturing data in their databases [Mark Albert, 2002]. Nonetheless, for instance, CNC manufacturers need to be fully convinced with the reliability and perfectness of STEP in order to put the G-Code away. On the other hand, several leading CAM software companies have made it possible for STEP-NC files to be used with their own software. This makes their users ready to participate in supply chains that are turning to global data

exchange standards to streamline the flow of digital information over the Internet. In the following section, Axiomatic design as the proposed methodology for developing a roadmap for universal platform will be explained.

3. AXIOMATIC DESIGN THEORY

In the late 1970s, based on his manufacturing experience, Nam P. Suh [2001] began the development and introduction of what is now so called, the axiomatic design (AD) approach. His main target was to establish solid and scientific fundamentals for product design and manufacturing. In AD, to establish a design problem, at the first stage, to satisfy the perceived needs, the design goals must be set. At later stage, the designs for the defined requirements are provided among which, the best design is chosen. [Suh, 1990]. These activities occur between and in different design domains such as customer, functional and design [Kim and Suh 1991]. The customer domain is where customer needs (CNs) reside. These needs must be mapped into the functional domain where in they are translated into a set of functional requirements (FRs). In design domain, design parameters (DPs) are selected to control/satisfy the FRs. Decomposition in each domain cannot be performed autonomously of the developing hierarchies in the other domains and decomposition follows a zigzag pattern between adjacent domains [Albano & Suh, 1994]. The relationship between FR and DP domain along with the design matrix to represent how a DP can satisfy an FR is illustrated in Figure 8.

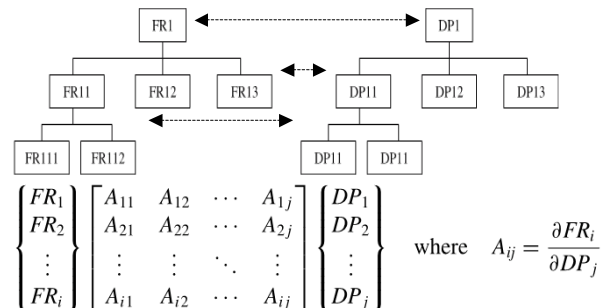


Figure8. FRs and DPs in Axiomatic design theory

In AD, the FRs must be independent and the best design is the one with the minimum content of information. These axioms are recognized as Independence Axiom Information Axiom, respectively [Suh 1990]. Along with these two axioms, eight corollaries, 26 general theorems, and 14 specific theorems have been developed to guide and evaluate the design problems [Thielman & Ge, 2006].

4 AD IN DESIGN PROBLEMS

Axiomatic design is quite excellent in that, multiple functional requirements can be methodically handled, whereas most design methodologies can handle only one functional requirement [Park 2006]. During the recent decade, this methodology has been used in three domains of (i) design for manufacturing, (ii) manufacturing processes, and (iii) manufacturing systems [Shirwaiker & Okudan, 2008], [Kulak

et al, 2005]. However, to deal with real problems, product and enterprise requirements have been separately considered [Yien 1998], [Almstrom 2000]. But it is not very well understood how the theory can be applied to implement a roadmap for production systems. Vallhagen [1994] has criticised Suh's original theory, claiming that the direct mapping (one to one relationship) is insufficient when designing a manufacturing system. [Vallhagen 1996a].

Yien and Tseng [1996] and Cochran [1994] dealt with manufacturing systems design problem in terms of AD, by defining their own domains. In a practical point of view, managers as well as engineers are inclined to focus on the solutions before the requirements are fully stated and realized [Almstrom 2005]. An analogy among different design problems including system design which is similar to roadmap design has been explained by Gebala and Suh [1992]. Although, this methodology is very useful to tackle the real design problems, explicit ontology definition and implementation of axioms measures are yet to be well thought-out by practitioners [Ge 2001].

5 IMPLEMENTATION OF THE UMP WITH AD

Based on what explained in section 2 about the specifications of a universal manufacturing platform for data integration, the functional requirements for implementing such a platform are defined. Then, DPs to satisfy these FRs will be provided and in order to represent the relationship between these two domains, design matrices are determined. In the axiomatic methodology terms, the top level is the main goal of the problem and labeled as FR_0 . At this level, to achieve the goal of an integrated manufacturing platform FR_0 is defined as follows:

FR_0 : Efficient communication throughout the enterprise production echelon

To meet this requirement, the first level in the design domain, is considered as follows:

DP_0 : Implementation of the universal manufacturing platform, UMP Production echelon encompasses three different levels (Figure 2). Therefore, FR_0 is classified into 3 levels as follows:

FR_1 : Product data integration in manufacturing level

FR_2 : Product data integration in manufacturing supports level

FR_3 : Product data integration in production control level

To satisfy these FRs, decomposition of DP_0 results into the following DPs:

DP_1 : Implementation an integrated platform in CAx chain

DP_2 : Implementation an integrated platform in Assembly and Automation

DP_3 : Implementation an integrated platform in production applications

As mentioned in section 2.1, in each level of the production echelon, one or two technological layers may be considered. In manufacturing and manufacturing supports levels, both application and device layers must be covered by the proposed platform while in production control level, product data exchange in application layer is dealt with. Consequently, the set of subsequent FRs along with their corresponding DP's are as follow:

FR_{11} : Integration in Application to Application DP_{11} : Utilizing the direct data exchange

FR_{12} : Integration in Device to Application DP_{12} : Utilizing the convertor interface

FR_{13} : Integration in Device to Device DP_{13} : Utilizing the intelligent controllers

FR_{21} : Integration in Application to Application DP_{21} : Utilizing the direct data exchange

FR_{22} : Integration in Device to Application DP_{22} : Utilizing the convertor interface

FR_{23} : Integration in Device to Device DP_{23} : Utilizing the intelligent controllers

FR_{31} : Integration in Application to Application DP_{31} : Utilizing the direct data exchange

As previously discussed, in this paper we mainly deal with the integrated platform in manufacturing level and since the other two levels follow the same solution, they would be ignored for further analysis. Design parameters for FR_j ($i > 1$) are the same as DP's for FR_j ($i = 1$). Hence, hereafter, manufacturing level including all the activities in CAx chain will be investigated. Figure 9 demonstrates how FR's (for $i = 1, j = 1, 2, 3$) are dependent on their corresponding DP's..

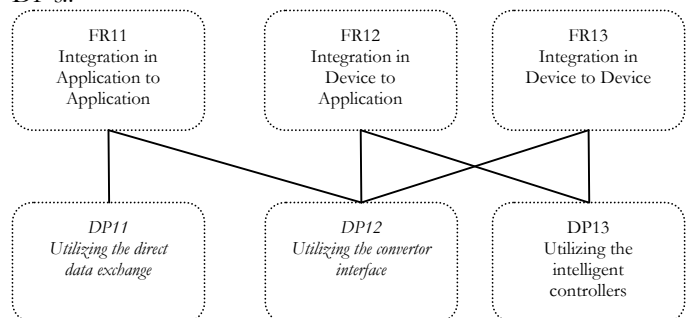


Figure9. Relationship between FR and DP domains, a coupled design

To mathematically represent the relationship between FR's and DP's, design matrices (DM's) are as follows:

$$\begin{Bmatrix} FR_1 \\ FR_2 \\ FR_3 \end{Bmatrix} = \begin{bmatrix} A_{11} & A_{12} & A_{13} \\ A_{21} & A_{22} & A_{23} \\ A_{31} & A_{32} & A_{33} \end{bmatrix} \times \begin{Bmatrix} DP_1 \\ DP_2 \\ DP_3 \end{Bmatrix}; (A_{ij}=0 \text{ for } i \neq j)$$

$$\begin{Bmatrix} FR_{11} \\ FR_{12} \\ FR_{13} \end{Bmatrix} = \begin{bmatrix} B_{11} & B_{12} & B_{13} \\ B_{21} & B_{22} & B_{23} \\ B_{31} & B_{32} & B_{33} \end{bmatrix} \times \begin{Bmatrix} DP_{11} \\ DP_{12} \\ DP_{13} \end{Bmatrix};$$

$$\{FR_{ij}\} = \begin{bmatrix} X & X \\ & X & X \\ & & X & X \end{bmatrix} \{DP_{ij}\}$$

$$(B_{13} = B_{21} = B_{31} = 0);$$

In order to satisfy the independence axiom, the design matrix must be decoupled or uncoupled. Coupled designs cannot be accepted since they violate the first axiom in the methodology (Suh, 2001). Therefore, considering the diagonal matrix of A , the set of $FR_{i=1,2,3}$ are fully independent and the first axiom has been fulfilled or the design is uncoupled. At the next stage, as shown by matrix of B , it is observed that this design is coupled because the matrix is not triangular. Since based on axiomatic design, coupled designs are undesirable; matrix B must be converted to a decoupled one. The matrix would become a triangular one in two different ways: setting $B_{32} = 0$ and obtaining an upper triangular matrix or setting $B_{12} = B_{23} = 0$ and obtaining a lower triangular matrix. In fact, eliminating B_{32} means in integration of device to device, utilizing a convertor interface is not allowed ($\partial FR_{13} / \partial DP_{12} = 0$). In the other way, applications cannot use convertor interface to communicate ($\partial FR_{11} / \partial DP_{12} = 0$) and integrating the applications with device would not be applicable ($\partial FR_{12} / \partial DP_{13} = 0$). To decouple this design, following the first way seems to be more reasonable since less change would be applied. Therefore, the new set of equations of FR's is as follows:

$$FR_{11} = B_{11} * DP_{11} + B_{12} * DP_{12} + B_{13} * DP_{13}$$

$$FR_{12} = B_{22} * DP_{12} + B_{23} * DP_{13}$$

$$FR_{13} = B_{33} * DP_{13}$$

This means by satisfying FR_{13} , FR_{12} and FR_{11} , respectively, the independence axiom become fulfilled and the uncoupled design is changed to a decoupled one. The new FR-DP relationships are illustrated in Figure 10.

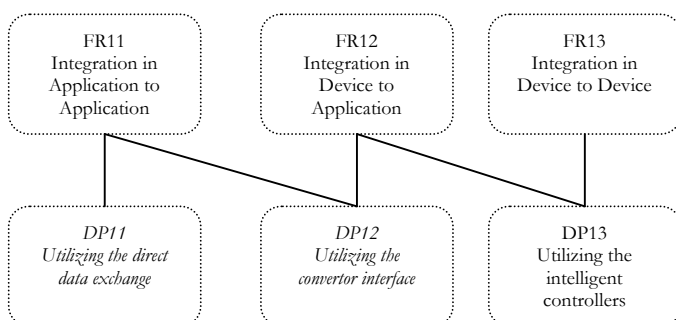


Figure10. Relationship between FR and DP domains, a decoupled design

In device side (e.g. CNC) applications may not be able to read and write through an interface due to the kind of used computers. Most of the devices work in dusty and noisy environment of shop floors and this is restriction in using a real computer as their controllers [Blecha & Bradac, 2003]. They may need their own controllers design specifically for their individual applications and resistant to some inconvenient conditions. These new controllers must be intelligent enough to operate independent of any interface. Using STEP-NC neutral format, some CNC controllers have been developed for very simple part geometries [Lee & Bang, 2006], [Xu & Newman, 2006], [Suh & Cheon, 2002].

6 DISCUSSION AND CONCLUSIONS

In this paper, using the methodology of axiomatic design, a roadmap to implement the integrated manufacturing platform was introduced. Referring to the decoupled design shown in Figure 10, two application programs are able to seamlessly communicate when they utilize a convertor interface or the direct data exchange. Interoperability in device to application is also realized by employing a convertor interface or an intelligent controller. The only requirement which is fulfilled by one design parameters is integrating the two device layers. As discussed in section 1, 2, the acceptable neutral format to be used as a direct data exchange is STEP and its relevant application protocols. On the other hand, STEP-based CNC controllers and STEP-based Robots are to be introduced in near future to realize the use of intelligent and format independent controllers in device side. However, since this dream needs more economic and technical justifications, convertor interfaces seems to be an appropriate solution for the time being. The design specification of a machining part may be restored as a neutral format (e.g. STEP 10303-203) and sent to the CAM software in which, STEP-NC file or STEP 10303-238 is produced. The outcome will be transferred to an A/D interface which converts the AP238 part 21 file into a G-Code file readable by the CNC machine. CNC may communicate its loaded AP238 file with a robot to handle the part. This could happen by utilizing a D/D interface or two intelligent controllers in CNC and robot sides. While developing comprehensive and integrative convertor interfaces like ORiN2 is still followed by researchers and parishioners, fully STEP-based communication will become more efficient in the future. This is due to its simplicity and integrity along with the huge cost and time for developing new different interfaces. As mentioned before, the main challenge is still investing on the new controllers for the variety of devices and equipments such as Robots, Conveyors, PLC's etc. In AD theory, based on the second axiom, the most satisfactory design is the one having the minimum content of information. For example, whether or not a shop floor invest on new interfaces or new STEP-in STEP-out softwares, these two solutions might be evaluated in terms of the information they require to be implemented. Such an evaluation is beyond the scope of this article and could be

considered by future researches. However, the universal platform bounded may go further to include the entire of the organizations.

7 REFERENCES

- [1] Albano, L. and N. P. Suh, "Axiomatic design and concurrent engineering", *Computer-Aided Design*, Vol. 26 (7), 1994.
- [2] Ali, L., Newman, S.T., Petzing, J., "Development of a STEP-compliant inspection framework for discrete components", *Proceedings of the Institution of Mechanical Engineers, Part B: Journal of Engineering Manufacture*, 219 (7), pp. 557-563, 2005.
- [3] ALMSTRÖM, P., "Development of Manufacturing Systems A Methodology Based on Systems Engineering and Design Theory", *Chalmers University of Technology Göteborg, Sweden*, 2005.
- [4] Almstrom, P., "UTILIZING AXIOMATIC DESIGN IN A MANUFACTURING SYSTEM DEVELOPMENT FRAMEWORK", *Proceedings of ICAD2000 First International Conference on Axiomatic Design Cambridge, MA*, ICAD045, 2000.
- [5] Álvares, A.J., Ferreira, J.C.E., Lorenzo, R.M., "An integrated web-based CAD/CAPP/CAM system for the remote design and manufacture of feature-based cylindrical parts", *Journal of Intelligent Manufacturing*, pp. 1-17, Article in Press, 2008.
- [6] Amaitik, S.M. and Kilic, S.E., "STEP-based feature modeller for computeraided process planning" *International journal of Production Research*, 43, 3087–3101, 2005.
- [7] Bhandarkar, M. P., Downie, B., Hardwick, M. and Nagi, R. "Migrating from IGES to STEP: one to one translation of IGES drawing to STEP drafting data", *Computers in Industry*, 41(3), 261±277, 2000.
- [8] Brecher, C., Vitr, M., Wolf, J. "Closed-loop CAPP/CAM/CNC process chain based on STEP and STEP-NC inspection tasks", *International Journal of Computer Integrated Manufacturing*, 19 (6), pp. 570-580, 2006.
- [9] Cochran, S., D., "The Design and Control of Manufacturing Systems", A Manufacturing Systems Design Methodology, *Proceedings of the 3rd CIRP Workshop on Design and Implementation of Intelligent Manufacturing Systems*, Tokyo. Thesis, Auburn University, Auburn, 1994.
- [10] Fuh, J. Y. H., Chang, C. H. and Melkanoff, M.A., "The development of an integrated and intelligent CAD/CAPP/CAFP environment using logic based reasoning", *Computer Aided Design*, 28, 217–232, 1996.
- [11] Gao, J. X., Aziz, H., Maropolous, P. G. and Cheung, W.M., "Application of product data management technologies for enterprise integration". *International Journal of Computer Integrated Manufacturing*, 16, 491–500, 2003.
- [12] Ge, P., Collaborative, "negotiation for early stage parametric design of mechanical systems", *PhD thesis, University of Southern California, Department of Mechanical Engineering, Los Angeles, CA*, 2001.
- [13] Gebala and Suh, "Research in Engineering Design Theory, Applications, and Concurrent Engineering", *Springer-Verlag New York Inc*:149-162, 1992.
- [14] Hardwick, M., Loffredo, D., "Lessons learned implementing STEP-NC AP-238", *International Journal of Computer Integrated Manufacturing* 19 (6), pp. 523-532, 2006.
- [15] Iwata, K., "Virtual Manufacturing Systems as Advanced Information Infrastructure for Integrating Manufacturing Resources and Activities", *Annals of the CIRP*, 46/1:335-338, 1997.
- [16] Kulak, O., Durmusoglu, M.B., & Tufekci, S., "A complete cellular manufacturing system design methodology based on axiomatic design principle", *Computers & Industrial Engineering*, 48(4), 765–787, 2005.
- [17] Li-Hong Qiao, Chun Zhang, Thu-Hua Liu, H.-P. Ben Wang and Gary W. Fischer, "A PDES/STEP-based product data preparation procedure for computer-aided process planning"
- [18] Li, Z., Kota, S. Virtual Prototyping and Motion Simulation with ADAMS", *Journal of Computer. Information Science Engineering, Journal of Computing and Information Science in Engineering*, Vol 1, No. 3, 276-280, 2001
- [19] Patil, L., Pande, S. S., "An intelligent feature- based process planning system for prismatic parts" *International Journal of Production Research*, 40 (17), pp. 4431-4447, 2002.
- [20] Owen, Jon, Bloor, M. Susan, "NEUTRAL FORMATS FOR PRODUCT DATA EXCHANGE: THE CURRENT SITUATION", *CAD Computer Aided Design*, 19 (8), pp. 346-443, 1997.
- [21] Proctor, Frederick M., Kramer, Thomas R. "Feature-based machining system using STEP Source", *Proceedings of SPIE - The International Society for Optical Engineering*, 3518, pp 156-163, 1998.

- [22] Rohan A. Shirwaiker · Güle. Okudan, “Triz and axiomatic design: a review of case-studies and a proposed synergistic use”, *Journal of Intelligent Manufacturing*, 19:33–47, 2008.
- [23] Shin, M.-K., Kim, Y.-I., Kang, B.-S., Park, G.-J., “Design of an automobile seat with regulations using axiomatic design”, , *Proceedings of the Institution of Mechanical Engineers, Part D: Journal of Automobile Engineering*, 220 (3), pp. 269-279, 2006.
- [24] Suh, N. P., “Axiomatic Design: Advances and Automations”, *Oxford University press*, 2001.
- [25] Suh, N. P. , “The principles of design”, *Oxford :Oxford University Press*, 1990.
- [26] Suh, S.H., Cho, J.H. and Hong, H.D., “On the architecture of intelligent STEP-compliant CNC”, *International Journal of Computer Integrated Manufacturing*, 15, 168–177, 2002.
- [27] Thielman, J., Ge, P., “Universal Linking of Engineering Objects”, *Journal of Engineering Design*, Vol.17, No. 1,1–16, 2006.
- [28] Vallhagen, “An Axiomatic Approach to Integrated Product and Process Development”, *PhD Thesis, Department of Production Engineering, Chalmers University of Technology, Göteborg*, 1996.
- [29] Vernadat F. B., *Enterprise Modeling and Integration*, Chapman and Hall, London, 1996.
- [30] Xu, X.W., Wang, H., Mao, J., Newman, S.T., Kramer, T.R., Proctor, F.M. and Michaloski, J.L., “STEP-compliant NC research: the search for intelligent CAD/CAPP/CAM/CNC integration”, *International Journal of Production Research*, 43, 3703–3743, 2005.
- [31] Yien, J. T., “Manufacturing Systems Design Methodology”, *Ph.D. Thesis, Hong Kong University of Science and Mechnology, Hong Kong*, 1998.
- [32] Zhanga, X, Wanga, J., Yamazakia, K., Morib, M., A surface based approach to recognition of geometric features for quality freeform surface machining, *CAD Computer Aided Design* 36 (8), pp. 735-744.
- [33] Zimmerman, J.U., Haasis, S., van Houten, F.J.A.M., “Session on Design: Universal Linking of Engineering Objects”, *Annals of the CIRP*, 51/1:99-102, 2002.