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Whether to Cast, Weld or Bolt – Learning Design for Manufacturing through a Graduation Project

Dr. Sangarappillai Sivaloganathan, United Arab Emirates University

Dr Sivaloganathan graduated from the University of Srilanka in 1976. After an year of post graduation train in the Railways he joined the Cement industry where he worked for ten years. He got his M.Sc. from University of Aston in 1981 and Ph.D. from City University London in 1991. He joined Brunel university in 1995 and worked there as a senior lecturer until he left Brunel in September 2011 to join UAEU. Dr Sivaloganathan was the founding Course Director for M.Sc. in Advanced Engineering Design at Brunel. He has published more than 50 papers in reputed journals and conferences. His research interests are Design Theory and Methodology, CAD and Applied FEA.

Whether to Cast, Weld or Bolt – Learning Design for Manufacturing through a Graduation Project

Sangarappillai Sivaloganathan, Aisha Abdulrahman, Shaikha ALDousari,
Abeer ALShamsi and Aysha ALAmeri

United Arab Emirates University
Department of Mechanical Engineering, PO Box 17555, Al Ain
United Arab Emirates
Sangarappillai@uaeu.ac.ae

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Abstract: Engineering Design of a product identifies a set of functions derived from a societal need and defines connected structures which as a whole deliver those functions. In this process it blends theory and design method into 'Design Approach' while technology, and working constraints form 'Design Realization'. Design for Manufacturing is the overlap of Design Approach and Design Realization which is characterised by (i) Design For Manufacture and Assembly considerations (ii) process considerations (iii) purpose of manufacturing (iv) available raw material forms and sizes and (v) other factors like work holding, available capability etc. For students getting ready to graduate, Design for Manufacturing is a new experience. This paper argues that Graduation Project provides a good opportunity for students to understand Design for Manufacturing. It considers the Graduation Project, designing and building a surgeon's operating table, by a group of four students from the UAE university, as a candidate to demonstrate this provision.

1 Introduction

Engineering Design is the use of scientific principles, technical information and imagination in the definition of a mechanical structure, machine or system to perform specified functions with the maximum economy and efficiency [1]. Eder [2] outlines that a designer must have certain types of knowledge and skill, and illustrates it with a schematic diagram which is given here in Figure 1.

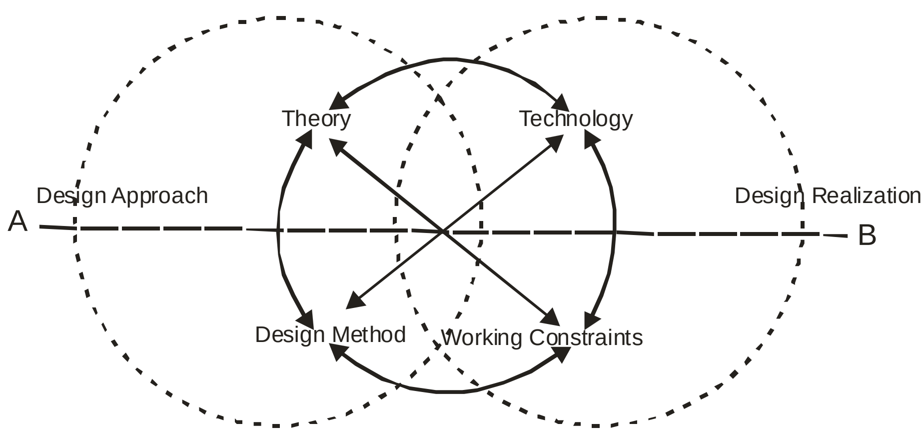

Figure 1: Designer's Knowledge [2]

Eder defines the components in the following way.

i. *Theory*: Mathematics and its applications to kinematics, dynamics, statics, energy, materials etc.

ii. *Technology*: Collection of manufacturing processes that may be used in manufacturing the product.
iii. *Design method*: The approach to a problem that is likely to lead to a successful solution
iv. *Working constraints*: The restrictions derived from economics, aesthetics, available space and time and the type of the artefact itself.

He further adds that theory and design methods, or the design approach, formulate the generation of a design solution which is theoretically sound without violating any laws of physics. Technology and working constraints or design realisation on the other hand shapes the design so that it can be manufactured efficiently and economically without sacrificing quality.

If Eder's diagram is divided by the line AB into two halves, the top part is where knowledge is inputted or taught through various courses at university. The bottom half is concerned with the choice of the appropriate component or chunk of the knowledge and its efficient use, and Graduation Project is aimed at this use which requires the integration of the four components identified by Eder. Design for Manufacture is the overlapping area (the lens in Figure 1) between the circles Design Approach and Design Realisation. Corrado Poli [3] states that Design for Manufacturing is a philosophy and mind set in which manufacturing input is used at the earliest stages of design in order to design parts and products that can be produced more easily and economically. It is a practice emphasising manufacturing issues throughout the product development process and the issues involved in the manufacturing of the designed object are considered explicitly with a view to influence the design. This paper outlines (i) the elements of this philosophy from literature (ii) how they were adopted for use in the graduation project where an operating table usable by surgeons was designed and built and (iii) the generic lessons learnt by the students from the experience.

2 Design Methodology

Engineering Design is the process of defining a layout or configuration and the details of parts and assemblies that as a whole would perform specified functions. The behaviour of the pieces and the theoretical calculations of their behaviour depend on the way they are used. For example a long structural member can be used as a tie, strut, column or a beam of several kinds and the behaviour and theory are different in each form. All these are taught in theory. Frank [4] rightly argues that to develop a successful product in the market the designer should possess both generic and specialist knowledge. In this context the generic knowledge is the theoretical knowledge and the specialist knowledge is the knowledge of the product which often is very much focussed and commercially sensitive. The concept of 'Function' introduced by the discipline of 'Value Analysis' [5] and brought to the design arena by Pahl and Beitz [6] has become a corner stone in design. Establishing the 'Function Structure' has been seen as a fundamental step in design methodology advocated by text books [6 7]. The functions performed by a product should contribute towards the fulfilment of a societal need. Mohd-Hashim [8] states that *functions are often expressed as verbs acting on nouns and are associated with function providers and function acceptors. For example 'hole LOCATE pin' and 'bearing SUPPORT shaft'* can illustrate the providers called 'Functors' and acceptors. These functors and acceptors can be sub-assemblies, parts or features depending on the level of abstraction employed at that stage. In a graphical notation, nodes represented by rectangles show the functors and acceptors and a circle/ellipse represents a function as shown in Figure 2.

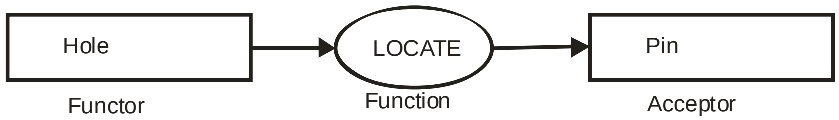

Figure 2: Schematic Function Representation

In summary engineering design of a product identifies a set of functions derived from a societal need and defines connected structures as functors and acceptors to deliver those functions. On the other hand all engineering structures realizing those configurations contain joined sections and these sections are in effect characteristics of their methods of manufacture and the design of the components making the configuration should utilize the beneficial properties, and design out the adverse properties of the chosen manufacturing process. Students in the GP course should therefore identify the need of the product and establish a set of functions and a skeletal structure delivering them which satisfies the need. The method of establishing this is described elsewhere [9]. The following sections describe how the skeletal structure or concept can be developed further into 'Design Realization'.

3 Design for Manufacturing

Design for Manufacturing is a philosophy and mind set aimed at designing parts and products that can be produced more easily and economically and a practice emphasising manufacturing issues throughout the product development process. The issues involved in the manufacturing of the designed object are considered explicitly with a view to influence the design. Issues normally considered include (i) DFMA considerations (ii) purpose of manufacturing (iii) forms and sizes of available materials (iv) the manufacturing processes involved (v) work holding during manufacturing and assembling (vi) available capability and (vii) the number to be manufactured. The following sub sections look at these more closely.

3.1 Design for Manufacturing and Assembly or DFMA Approach

Manufacturing Operations can be grouped into two categories, fabrication and assembly. In fabrication the piece part is manufactured and in assembly the piece parts are assembled into assemblies and they are assembled together to form the product. The pioneering work in this area, attributed to Boothroyd and Dewhurst [10], specifies guidelines to improve the design to save on cost and time. The guidelines are like (i) reduce the number of parts by combining functions (ii) use modular design (iii) design so that assembly operations are in one direction (iv) design in such a way that assembling in the correct direction only is possible and (v) minimize the use of fasteners. A good list of DFM guidelines is given by Chang T.C. et al [11]. Similarly Design for Assembly, DFA, aims to simplify the design so that assembly cost is minimised. Often DFA includes the analysis of part design as well. Otto and Wood [12] and Ulrich and Eppinger [13] cover the topic well. The guidelines should be considered during the conceptual and embodiment design stages and the resulting design should be subjected to a systematic review for DFMA.

3.2 The purpose of Manufacturing

Physical models called prototypes can be made to resemble the actual artefact at several different levels. Ullman [7] defines four levels of prototypes during the development of a commercial product in the following way:

i. *Proof of Concept Prototype*: Focuses on developing the function of the product for comparison with the customer's requirements in specifications. It is intended as a learning tool and exact geometry, materials, and manufacturing process are usually not important. It can be built out of paper, wood, parts from a junkyard or whatever is handy.

ii. *Proof of Product Prototype*: Developed to help refine components and assemblies. Geometry, materials and manufacturing processes are as important here as the functions. Rapid Prototyping can be useful here. The prototype may be of the exact geometry but might have been manufactured using a different process than what was intended for actual production for sale.

iii. *Proof of Process Prototype*: Used to verify both the geometry and manufacturing process. Exact materials and manufacturing processes are used to develop samples for functional testing.

iv. *Proof of Production Prototype*: Used to verify the entire manufacturing process. This prototype is the result of preproduction run, the products manufactured prior to production for sale.

A proof of production prototype agreeing with the specifications is essential for a company to start producing and selling the product and ramp up this activity. But in a graduation project the end result required at best is between proof of product prototype and poof of process prototype. The designers therefore have to consider the commercially viable manufacturing process and the process that is viable within the university environment to produce a proof of product concept.

3.3 Form and Sizes of Material Available

Metallic materials are available only in standard forms such as square, rectangle, channel, and angular sections and plates of different thicknesses with different cross sectional dimensions. The designer is restricted to use only these forms and sizes if casting or forging processes are excluded. When the quantity to be manufactured is just one, the choice on sizes is further restricted by variety reduction considerations.

3.4 Designing for the Manufacturing Process

Manufacturing processes in general offer certain benefits and restrictions. In this project the processes considered are casting, welding and bolting machined pieces and they are discussed in the following sub-sections.

3.4.1 Design for Casting

Metal Castings offer two unique and desirable design advantages: (i) metal mass can be located exactly where it is needed and (ii) complex, three-dimensional geometry is readily created [14]. In addition the number of piece parts can be reduced by combining them into one complex piece. However, the casting has to be designed to yield the piece part required for the product with due consideration for (i) solidification shrinkage (ii) solid shrinkage (iii) pouring temperature (iv) fluid flow (v) heat transfer considerations (vi) use of chills (vii) fluid life and (viii) gating and feeding system design. There are many casting processes such as sand casting, die casting, investment casting etc. Each process has its operating parameters and resulting product characteristics. A typical casting design consists of the features parting, core, mould, feeders and gating system. Software systems capable of analysing and making suggestions [15] on the suitability and dimensional changes have made design for casting an integral part of detail design.

3.4.2 Design for Welding

Welding is the process of joining together two pieces of metal where appreciable inter-atomic penetration takes place and integrating crystals form at their original boundary surfaces. From a design point of view it has the advantage of producing complex objects from standard sheet metal pieces. There are many types of welding including Metal Arc, Atomic Hydrogen, Submerged Arc, Resistance Butt, Flash, Spot, Stitch and Stud. Welding is a specialist process and experts should be consulted when dealing with complex parts. However for normal jobs there are guidelines [16-18] on the choice of the process and the type of preparation of the pieces to be joined. But one fundamental criteria is that the pieces to be welded must be from standard stocks to minimise further processing and the design should not place excessive demands on the joint during operation and the process must be simple.

3.4.3 Bolting and Riveting

This again is a process of joining of pieces of standard sheet metal to form complex objects. Before welding was invented this was the main process used for making complex objects and the Victorian Iron Bridges all over the Commonwealth are good examples of riveting. The main design criteria are the availability of standard material, ability of the bolt or rivet to withstand the load during service and a suitable manufacturing method.

3.5 Other important issues

i. *Work Holding*: Depending on the process chosen there will be several instances where parts have to be held in place when some process such as welding, bolting or machining has to be carried out. The design should accommodate these requirements. In the same way the sub assemblies have to be assembled together and the design should provide locating and work holding facilities. If fixtures are needed they have to be fabricated too.

ii. *Process Capability*: The resulting characteristics are very important in the choice of processes. For example for cutting, gas flame cutting, plasma cutting, laser cutting and water jet cutting can be used. Water jet cutting provides good cuts with low rms values and strain free regions. But the process is not widely available. Plasma cutting is widely available but the finishes are poor requiring corrective machining on hardened material.

iii. *Available Capability*: This includes the available machinery and equipment and the skill level of the operating staff.

iv. *Number to be Manufactured*: This will dictate the use of standard accessories and machines and inhibit development of special fixtures and wooden patterns for castings.

4 The Case Study

The case study is the design and development of a surgeon’s operating table. United Arab Emirates is developing fast and is planning to invest heavily in healthcare by building more new hospitals. The motivation for this project came from the desire to build supporting technical capability. Following the identification by Frank [4] the first task carried out by the students was to visit a local hospital, learn the operating table in use and conduct a design interpretation. This provided the level of knowledge required to embark on the design task. Though identifying clinical, health care staff, legal and the company requirements are fundamental in the planning stage this work was restricted to obtaining the requirements of the healthcare staff due to time constraints. The students followed a design process model similar to the one by Ulrich and Eppinger [13] and established mission statement, customer requirements (verbatim) and needs, function structure, target specifications, conceptual design and selection and refined and firmed up specifications. The concept was developed further into an embodiment design as shown in Figure 4 and presented as part of the outputs from Graduation Project 1 course [16]. In the second part of the course, Graduation Project 2, the students developed the design further and built the prototype. The design process model followed by them is given in Figure 3.

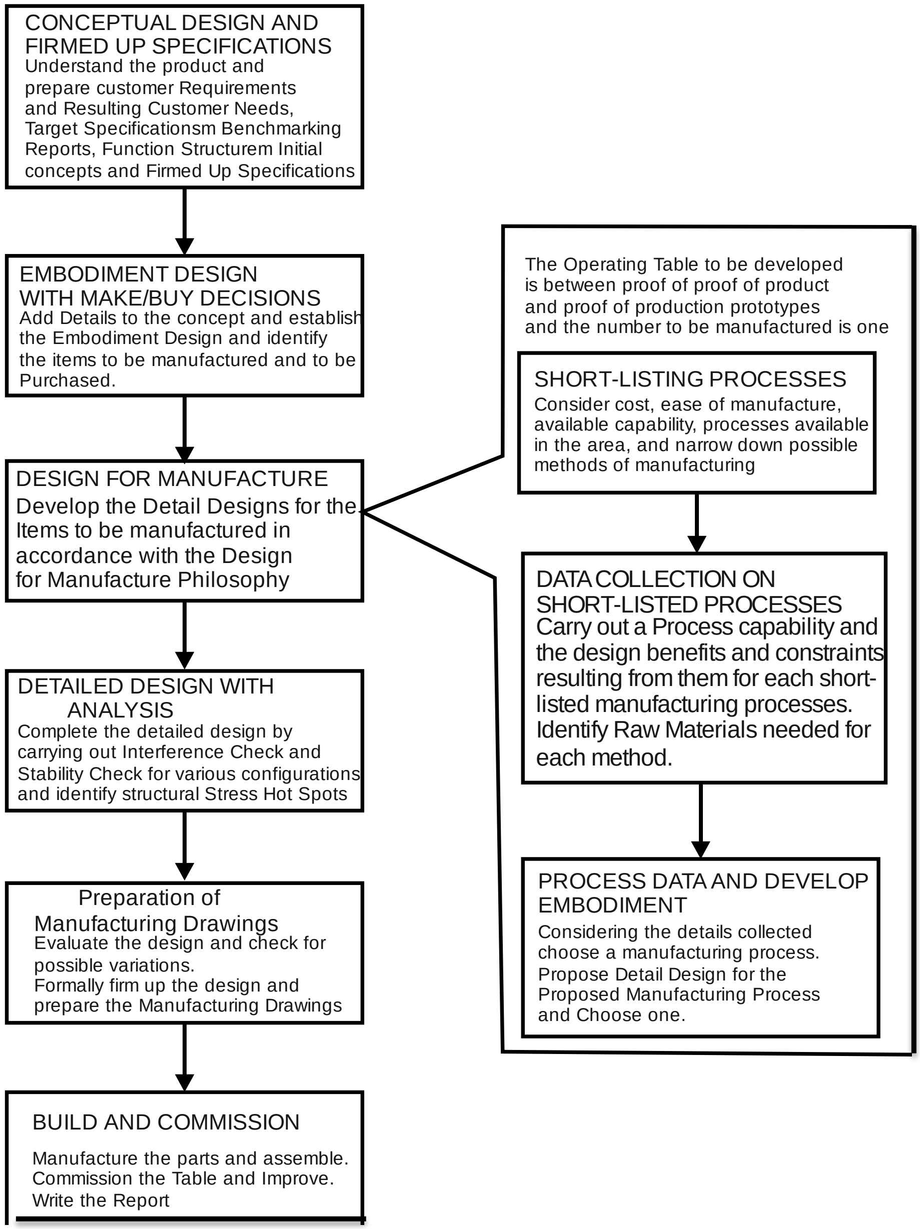

Figure 3: Design Process

4.1 Embodiment Design

The embodiment design consisted of fifteen subassemblies including the hydraulic, control and electrical powering systems. The hydraulic system consists of cylinders, piping, pump, valves and reservoir. At an early stage itself it was felt that this could be purchased from outside suppliers. The electrical powering system consists of a 12V battery and the charging unit. These again are items that are to be purchased from outside. Out of the remaining twelve, the head, hip and leg sections were combined to form a single torso section to minimise the work. The embodiment design is shown in Figure 4.

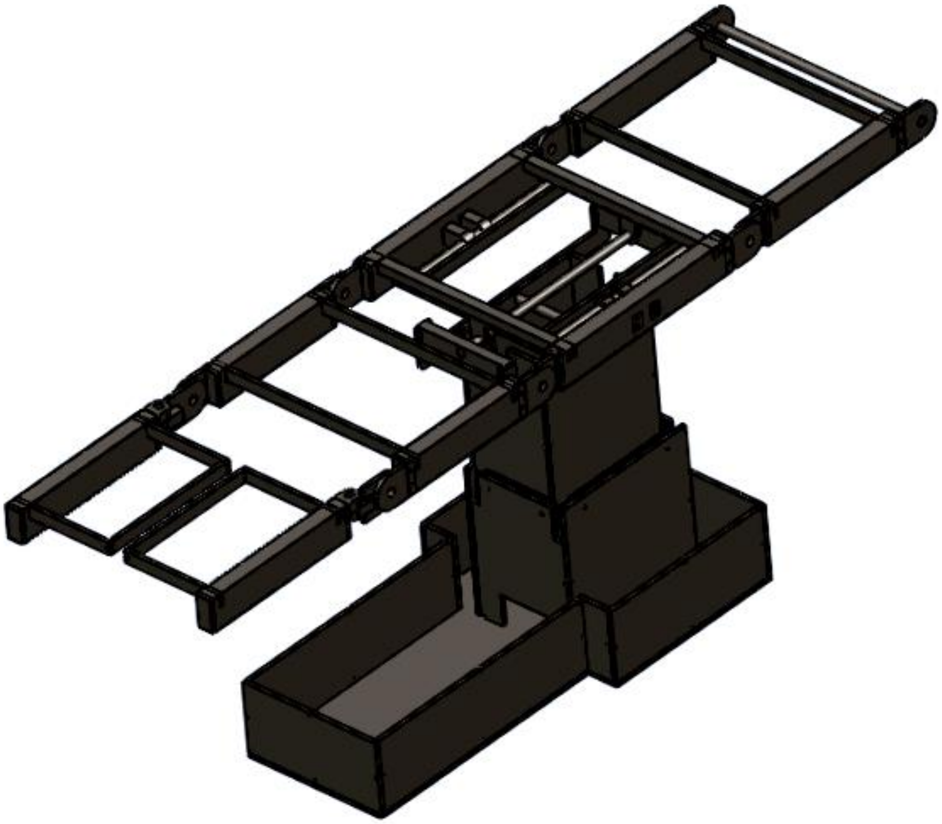

Figure 4: Embodiment Design

4.2 Design for Manufacture and Detail Design

The components to be designed and manufactured are (a) base (b) casing and column proving height variation (c) lower plate giving the inclination (d) upper plate giving the tilt and (e) the torso section carrying the patient load and transmitting it to the column. Casting, welding and bolting were the manufacturing processes that were considered. The end result or deliverable anticipated is a proof product prototype and the quantity to be manufactured is one. With these in the background the principles identified in section 3 were applied. Table 1 summarises the considerations for narrowing down the choice of process. From this analysis casting was ruled out. Welding seemed to be the chosen process but needed extra funding to do outside. The students were trying to get support from outside but nothing was forthcoming at that stage. Based on the available capability bolting was chosen.

4.2.1 Detail Design for Bolting and Product Realization

Detail Design is the process of incorporating all parts and features required. The first decision that had to be taken was the choice of raw materials. Use of 4 mm plates were considered at the beginning. But for the design for bolting five millimetre bolts were chosen. This meant that the plate should be 10 mm in thickness. It was therefore decided that all parts would be made up from 10 mm plate wherever possible. $40\,mm \times 80\,mm \times 1.5\,mm$ box sections were chosen to be used as beams in the bed sections and $25\,mm\emptyset$ bar was chosen to be used as shafts. A 1.5 mm thick plate was used as the cover for the base. Nylon wear pads were chosen to facilitate smooth up and down motion of the column. A total of 54 parts were required for the complete design and out of them 34 were to be cut from 10 mm thick plate. The complete design is given in Figure 5.

At this point in time the students managed to get sponsorship from Abu Dhabi Ship Building, ADSB, who agreed to provide the material and the cutting services. They used plasma cutting which meant the cut was not smooth. The pieces were machined and assembled at the

University. But getting the required number of bolt holes proved a herculean task. The design however was suitable for manufacture by welding. Again ADSB came to the rescue and the product was welded using their TIG welding facility and sand blasted. If the design was carried out for welding from the inception the column could have been made with thinner plates. Machining the pieces required proved too much for the Graduation Project and a simple bed section replaced the four sections shown in the design.

Table 1: Analysis of the Processes

Process	Analysis
Casting	Easy to provide more material in the base for low centre of gravity and resistance to toppling when attachments go outside the wheel-base. Choice of process will provide required surface finish. Casing and base can be combined. Aesthetic features can be incorporated. In spite of these advantages casting requires a pattern which is costly to produce a single piece and the product requires specialist 'casting design expertise' because of large surface areas. The capability within the university for casting is limited and the work has to be outsourced.
Bolting	Starts with two initial constraints (a) must be from available plate thickness (b) thickness should be sufficient to have reasonably sized bolts. Since the quantity to be manufactured is only one, the thickness of plates used as far as possible should be the same throughout the product. Cutting the plates to the required shapes is an important process. The university did not have the capability and this has to be done outside. The university however has a good vertical machining centre and this could be used whenever possible. The material chosen was stainless steel and hence carbide tools would be needed.
Welding	Starts with the initial constraint: must be from available plate thickness. Since the quantity to be manufactured is only one, the thickness of plates used as far as possible should be the same throughout the product. Similar to bolting cutting the plates to the required shapes is an important process. All other considerations were similar to those for bolting. Again the capability for welding in the university workshop is limited and the job has to be outsourced restricting students' learning experience.

5 Generic Lessons

i. The first and foremost lesson was the realization and understanding that '*Design for Manufacturing is a philosophy and mind set in which manufacturing input is used at the earliest stages of design in order to design parts and products that can be produced more easily and economically*' as defined by Poli [3]. The detail design was effectively led by design for manufacture considerations.

ii. The design obeyed many of the DFMA guidelines from the inception. Part counts were minimised wherever possible within the capability of the chosen manufacturing process. Assembling process strictly adhered to the guidelines and the product design was carried out with the assembling process in mind.

iii. The students realised that knowing the strengths and weaknesses of candidate manufacturing processes is a fundamental requirement for design. They also realised that process capability is a crucial factor when choosing a manufacturing process.

iv. Another realisation is the importance of the available capability in process selection and hence in design. For instance number of tool breakages varied significantly between operators.

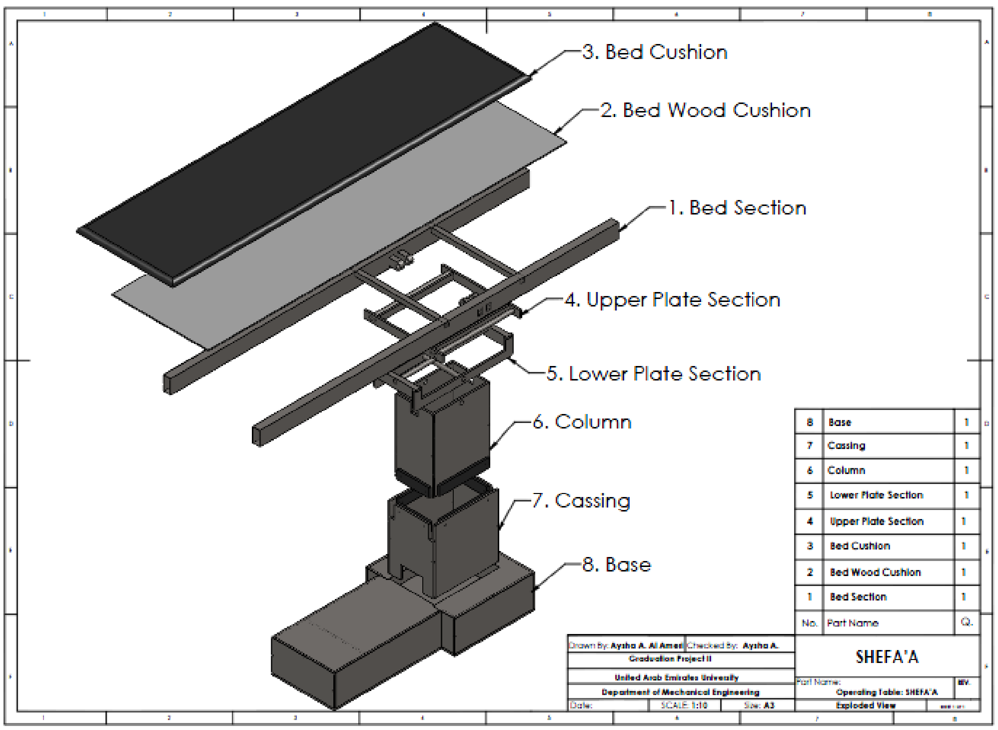

Figure 5: Complete Design of the Operating Table

6 Conclusions

Graduation Project is found to be a suitable mechanism for students to learn systematic design process and the practice of design for manufacturing. Restrictions arose from, factors like available sections, process capability, work holding methods and available capability. The project demonstrates that *Design for Manufacturing is a philosophy and mind set in which manufacturing input is used at the earliest stages of design in order to design parts and products that can be produced more easily and economically*.

References

1. Feilden G.B.R., Engineering Design, Her Majesty's Stationary Office, London 1963.
2. Eder W.E., Definitions and Methodologies, in The Design Method, Edited by Gregory S.A., Butterworths, London 1966.
3. Poli C, Design for Manufacturing, A Structured Approach, Elsevier Inc, 2001.
4. Frank D., The Importance of Knowledge Management for BMW, Keynote Address, International Conference on Engineering Design, Technical University of Munchen, Germany 1999.
5. Fowler T.C., Value Analysis in Design, Van Nostrand Reinhold New York 1990.
6. Pahl G. and Beitz W and Wallacw K., Engineering Design: A Systematic Approach, 2nd Edition, Springer 1995.
7. Ullman D.G.,The Mechanical Design Process, 3rd Edition, McGraw Hill, Singapore 2004.
8. Mohd Hashim, Using Functional Descriptions to Assist the Redesign Process, PhD Thesis, Department of Mechanical Engineering, University of Leeds, UK 1993.
9. Sivaloganathan S., Abdulrahman A., ALDousari S., ALShamsi A. and ALAmeri A., Design of Next Generation Products by Novice Designers Using Function Based Design Interpretation, Proceedings of ICoRD'13, IITMadras, Chennai India, January 2013.
10. Boothroyd G., Knight W.and Dewhurst P, Product Design for Manufacture and Assembly, 2nd Edition, Marcel Decker Inc 2002.
11. Chang T.C., Wysk R.A. and Wang H.P., Computer Aided Manufacturing, Second Edition, Prentice Hall, 1998.
12. Otto K. and Wood K. Product Design, Techniques in Reverse Engineering and New Product Development, Low Priced Edition, Pearson Education, Dorling Kindersley (India) Ltd, New Delhi 2006.
13. Ulrich K. And Eppinger S., Product Design and Development Third Edition, Tata McGraw Hill Edition, New Delhi 2005.
14. Stoll H.W. Casting Design Issues and Practices, Proceesdings Materials Solutions Conference 98 on Aluminium Castings
15. Ravi B., Creese R.C., and Ramesh D., Design for Casting – A New Paradigm for Preventing Potential Problems, Transactions of the American Foundry Society, Volume 107, 1999.
16. http://homepages.cae.wisc.edu/~me349/lecture_notes/welding_guidelines.pdf Visied on 15-12-2012.
17. http://www.metalwebnews.com/image/casting-guidelines.pdf visited on 14-12-2012.
18. Crow K., Design for Manufacturing Guidelines, Visited on 23rd November 2012. http://www.npd-solutions.com/dfmguidelines.html
19. Abeer A., Aisha A., Aysha A. and Shaikha A., *Design and Development of a Simple but World Class Operating Table*, Graduation Project Report, Department of Mechanical Engineering, United Arab Emirates University, UAE 2012.

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