Session 463685

Model-Make-Measure: Connecting the studio to the workshop

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Learning Objectives

- An approach to educating Design for Manufacture (DfM)
- Applying software tools in an iterative design and fabrication workflow
- Using Fusion 360 in a "Design for sand-casting" workflow
- Student group project collaboration with Fusion Team

Description

This industry talk charts a chapter in the story of UCL @ HereEast, a new education and research facility set-up in Stratford in the east-end of London that opened in 2018. It hosts a new masters course in Design for Manufacture (DfM) uniquely within a School of Architecture. Equipped with industrial robotics, CNC milling and turning machinery, folding, forming, laser-cutting, 3D-printing supported by a metal and wood fabrication workshop and facilities for component assembly and metrology, UCL @ HereEast strives to cultivate an environment where groups of student designers can learn to negotiate across the interface between the design studio and the point of industrial production.

This talk asks: how might the well-established methods for industrialised manufacturing that are prevalent in automotive and aerospace be used in the design of construction projects? This question is explored through an approach of "model-make-measure" in which students directly engage with the properties of materials and the effect that fabrication processes have on its material performance and dimensional variability. The feedback this approach creates between intent and outcome becomes the basis for evaluation and discussion, triggering opportunities for novel design outcomes. It also suggests workflows, methodologies and user skill-sets that are transferrable to the construction industry to aid improvements in the delivery of buildings.

Speaker

I am an associate professor of architecture investigating the design and engineering of low-energy passive devices for buildings. I trained as an architect and after a decade in practice retrained as a research engineer. I built on my experience in practice to work on a range of research projects applied to the built environment including passive downdraught ventilation, movable thermally-insulated window shutters,passive thermal actuator mechaniams, bioreceptive porous concrete and the development of bi-metallic operated window-blinds.

Introduction and context

I have a research interest in the challenges of bringing industrialized manufacturing to the construction industry. This is motivated by the long-standing observations that have been made about the characteristics of the construction industry with its client, team of design consultants and contractor structure, adverserial procurement processes, complicated supply-chains, fragmented delivery methods and operational processes e.g. (Egan, 1998). The results of these analyses have generally shown that the construction industry exhibits poor levels of productivity, high levels of waste and rework often due to the poor quality and coordination of design information leading to delays in completion and costly disputes between parties.

Equally long-standing observations have been made about similarities that can be drawn between the industrialised construction of housing and automotive production (Gunn, 1996). Where benefits can come from a component-based approach, with a systematic decomposition of a whole construction (or product) into assemblies and sub-assemblies in which the components are interchangeable within well-defined and coordinated dimensional relationships.

It is arguable that this situation will be difficult to improve if there remains a significant digital divide in the practice of translating design information to fabrication data. Yet a recent survey assessing the level of digitisation in the global construction industry against 27 metrics found it to be the *second lowest* out of 22 other major sectors of industry (McKinsey, 2015).

It is also arguable how best to bridge the digital divides that are found between design intentions and the fabrication data needed for its manufacture, and how best to teach the requisite skills and cultivate progressive working practices that address the limitations that the surveys have identified. As well as to adopt principles and techniques that have been shown to offer continued improvement. This industry talk presents projects from a new masters in Design for Manufacture (DfM) that is uniquely offered within a school of architecture at its new 3500m^2 facility dedicated to supporting manufacturing research and education in UCL @ HereEast.

FIGURE 1: THE HEREEAST SITE IN STRATFORD EAST LONDON (UK)

A place for Manufacturing and Design Exchange

During two and half years of teaching DfM I have been exploring the dialogue between software tools used to represent design intention and its relationship to the needs of producing manufacturing data for the processes involved in its fabrication as well as for its assembly.

The DfM course is fortunate to have access to a facility with an ecosystem of fabrication processes including; 3D printing, robotic fabrication, a range of CNC machinery for milling, routing, turning, folding, as well as felting, glass forming, welding, adhesion application, steam-bending and metal casting. Led by its technical director Peter Scully and known as the "Bartlett Manufacturing and Design Exchange" or B-MADE, it has been the physical place where the design studio culture of DfM meets the workshop culture of direct hands-on engagement with both materials and the range of fabrication processes that are available.

FIGURE 2: FACILITIES FOR INDUSTRIAL ROBOTICS AND CNC MACHINERY

FIGURE 3: PANORAMA OF THE SHARED GENERAL FABRICATION SPACE IN UCL @ HEREEAST

An approach to educating Design for Manufacture (DfM)

A design for manufacture education involves more than learning how to reconcile the differences between an ideal digital representation of your design idea and the physical reality of what you can make with the materials and machinery available to you together with your level of skill and experience of making. Instead of solely a process of translation, this course aims to teach design for manufacture as a creative dialogue between design and processes of making by acknowledging how the act of making can critically inform the assumptions in design intent.

For this dialogue to take place, the design studio needs to enter into purposeful conversation with the workshop, in order to be effective any sources of friction need to be reduced, including in the software tools that translate data between the two. Fusion 360 was selected as part of a software palette for its end-to-end design and manufacturing workspace to support the fluid flow between geometry and fabrication information as well as feedback from inspection metrology.

However, there are significant differences between these two cultures, the design studio is characterised by conversations and critical reviews or “crits” in which work-in-progress is discussed around sketches, models, 1:1 prototypes, animations, simulations and software code.

FIGURE 4: STUDIO "CRITS" REVIEWING WORK-IN-PROGRESS AND DEDICATED FUSION 360 SKILLS CLASSES

Whereas the workshop culture of UCL @ HereEast closely resembles that of a factory environment, so by physically connecting the design studio culture to the workshop we aim to promote and facilitate a dialogue between digital design representation and physical making.

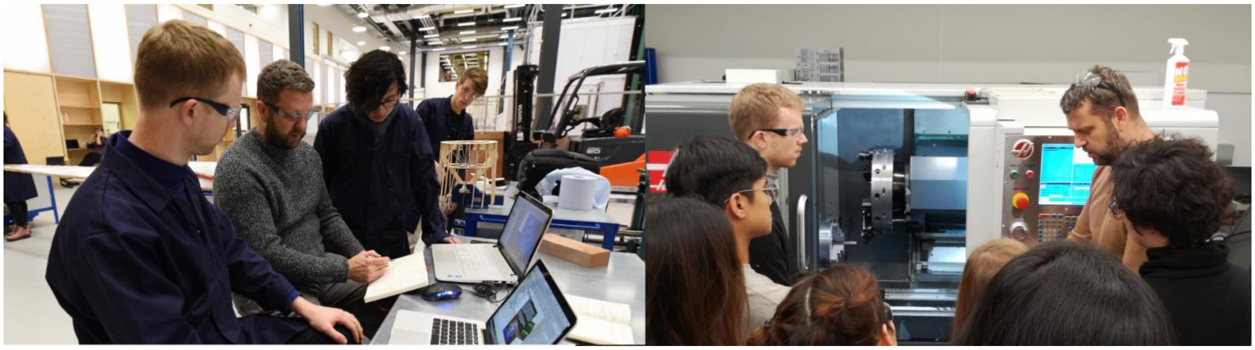


FIGURE 5: DFM STUDENTS IN THE WORKSHOP AND MACHINE-SHOP ENVIRONMENT

Design for Sand-Casting

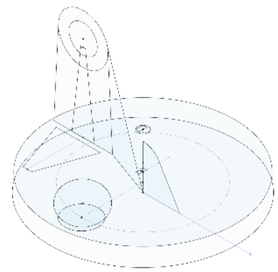
Casting metals is an ancient fabrication technique, with the earliest known example being a copper frog dated 3200 B.C. from Mesopotamia and large-scale casting can be traced back to the production of cast iron in China around 700 B.C. (Ravi, 2015). The fabrication process of casting light-alloy metals presents the knowledgeable designer with tremendous opportunities for making components that offer structurally strength and functionality while also affording sculptural expressiveness. Sand-mold casting is a simple technique that is accessible with minimal equipment in a simple workflow for creating the NNS (Near Net Shape) of a part.

Figure 6 shows an Aluminium casting for the “Pavilion for the Centennial of Aluminium” in Paris by the famous 20th century French constructor Jean Prouvé. Made from a mirrored two-part casting, it connects the roof and vertical structure, supports the roof surface, incorporates fixing-points for rainwater goods and banner pole support. It is an example of how the considered design of a light-alloy metal casting can be multi-functional and as in this case an interchangable module that was repeated 228 times in its original construction.

In this case-study success requires an understanding of the process to evaluate the feasibility of a pattern geometry within the constraints of achievable mold shape, the solid CAD model representation and analysis tools in Fusion 360 have been used in the following example.

FIGURE 6: DETAIL OF CASTING FOR THE JOINT BETWEEN ROOF AND VERTICAL STRUCTURE FROM THE “PAVILION FOR THE CENTENNIAL OF ALUMINIUM” IN PARIS DESIGNED BY JEAN PROUVÉ

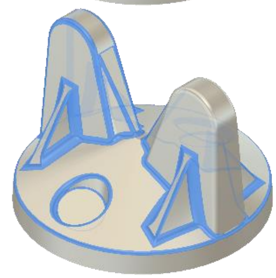
Modeling and simple analysis in design for sand-casting



The modeling features and analysis tools in Fusion 360 were used as digital aids in a design for sand-casting workflow as follows:

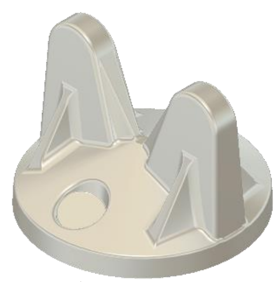
- The support for “User Parameters” in Fusion 360 enabled the geometric relationships between the features of the part to be comprehensively described. As the design developed these could be adjusted in response to a deepening understanding of the process constraints

- A closed boundary-represented solid geometry allows the careful study of how much variation in the three-dimensional thickness exists through the casting. The Inspect “Section Analysis” command was used extensively to avoid parts of the component becoming thinner than the minimum castable thickness as well as abrupt changes in thickness

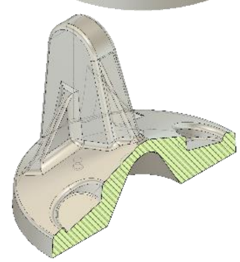


- Generous fillets were applied between the primary geometric forms to aid the flow of liquid metal around the mold’s cavity and reduce defects such as hot tearing

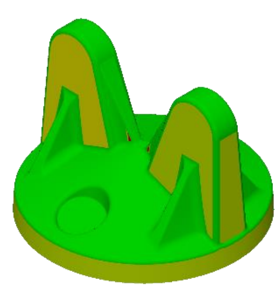
- The application of an appropriate draft angle to all the vertical surfaces and using the Inspect “Draft Analysis” command to visualize its distribution to check for locations that would impede removal from the mold. The draft angle applied was 2.5°



- Acknowledging that parts cast using the gravity sand-mold process exhibit shrinkage as the part solidifies and cools, the amount of shrinkage was be approximately compensated for by modelling a point using the Inspect “Centre of Mass” command and applying a uniform scaling factor of 5/32” per foot for Aluminium alloy of small size with a simple geometry after p. 202 in (Ammen, 1985).



- Using the correct “Physical material” assignment and component properties command it was straightforward to extract the mass of Aluminium (kg) needed for both the cast component and the risers and runners to match with the capacity of a crucible and furnace combination.



- The solid geometry was then exported as an *.stl file for 3D printing a dimensionally accurate pattern with a high-resolution (12.5μm in the X-Y axis on an Ultimaker 3)

Making a series of castings

Using the basic NNS in this simple workflow and taking advantage of the User Parameters in Fusion 360, the geometry was fully-constrained and then values adjusted iteratively using feedback from the draft analysis, section thickness measurement and total mass of cast. The Import/Export parameters (csv) add-in was then used to share these values between design files for a series of castings to suit different structural node geometries for joining together the ends of roundwood timbers was derived with one, two, three and four eyelets features as shown in the left of Figure 7.

When a balance was found between the parameter values, an *.stl file of the shrinkage compensated pattern was sliced in Ultimaker CURA software and 3D printed, then sealed from moisture ingress while in the green-sand mold and finally cast using a small-crucible foundry.

An advantage of fabricating this NNS in Aluminium using sand-casting is that 73% of material was saved that would have been removed by subtractive CNC milling from a cylindrical stock enclosing the same shape. While a compromise is made with the surface finish of a casting straight for the sand-mold compared with milling, we where pleasantly surprised by the consistency of the quality. We were more concerned with achieving the required tolerance on coordination of fixing holes and their centre positions, in general accepting the ±1mm dimensional variation, for the shaft that connects the nodes precision was projecting onto the case with post-cast milling only in those limited areas where needed.

FIGURE 7: 3D PRINTED PATTERNS FINISHED CONNECTOR NODE CASTINGS AND PARAMETRIC VARIATIONS (CASTINGS MADE BY MELIS VAN DEN BERG)

Designing movable building components

Given that buildings are exposed to prevailing meteorological conditions that are in a state of continual change, this case-study explored the design of a mechanism for building facades with variable performance that responds to the extremes of the prevailing environement between overcast and clear-sky sunlight. This case-study applied the mechanical design features of Fusion 360 software to develop and prototype an adjustable sun-blind operated by a novel passive thermal actuator device that is activated by absorbing solar energy by the greenhouse effect inside a micro-enclosure made of borosicilate glass 3.3. The design challenges included the need for robustness, a continuous thermal-break around the actuator, damping the wind-induced load on the sun-blind blades. As well as an approach to assembly and disassembly where each material type can be separated at the end-of-life into recoverable waste streams.

The project used Fusion 360's hybrid approach to modelling with components within and linked into sub-assemblies nested into assemblies to efficiently model the modular design. The tolerances required to ensure the fit of mechanical components made extensive use of the close-coupling between Fusion 360 design and manufacture workspaces.

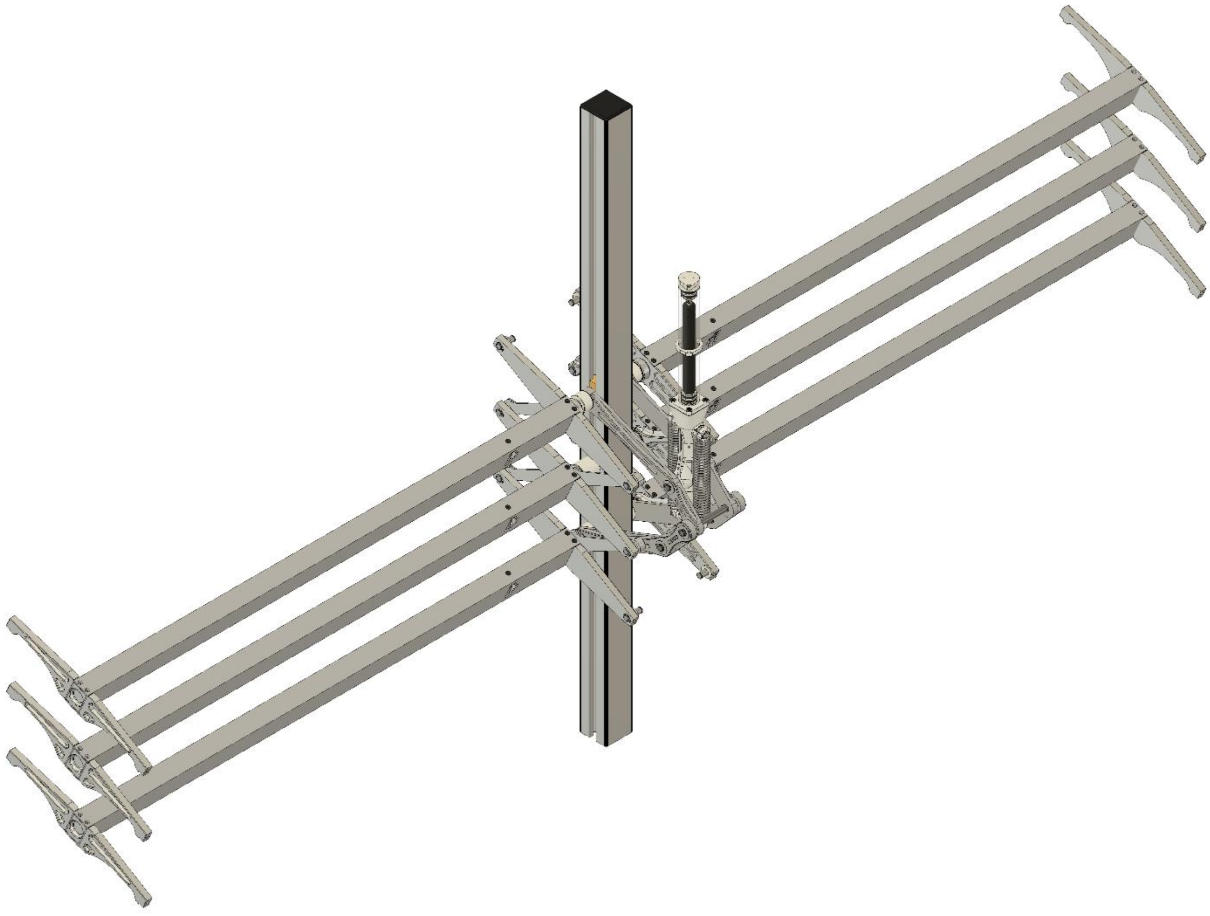


FIGURE 8: PASSIVE THERMAL ACTUATOR-OPERATED SOLAR BLIND MECHANISM FOR SHADING BUILDING FACADES (FUSION 360 FULLY ARTICULATED ASSEMBLY MODEL WITH SUN-BLIND BLADES OMITTED FOR CLARITY)

The judicious use of the Joint Origin command to specify the 3D location of each coordination point and its associated plane proved critical for developing this mechanism. It was used to resolve the degrees of freedom in movement between components and specify the datum for accommodating the direction of tolerance. The inspect "Section Analysis" command was used extensively to develop the mechanism linkages, assess the dimensional relationships between components as well as to detect and resolve clashes and clearances between moving parts.

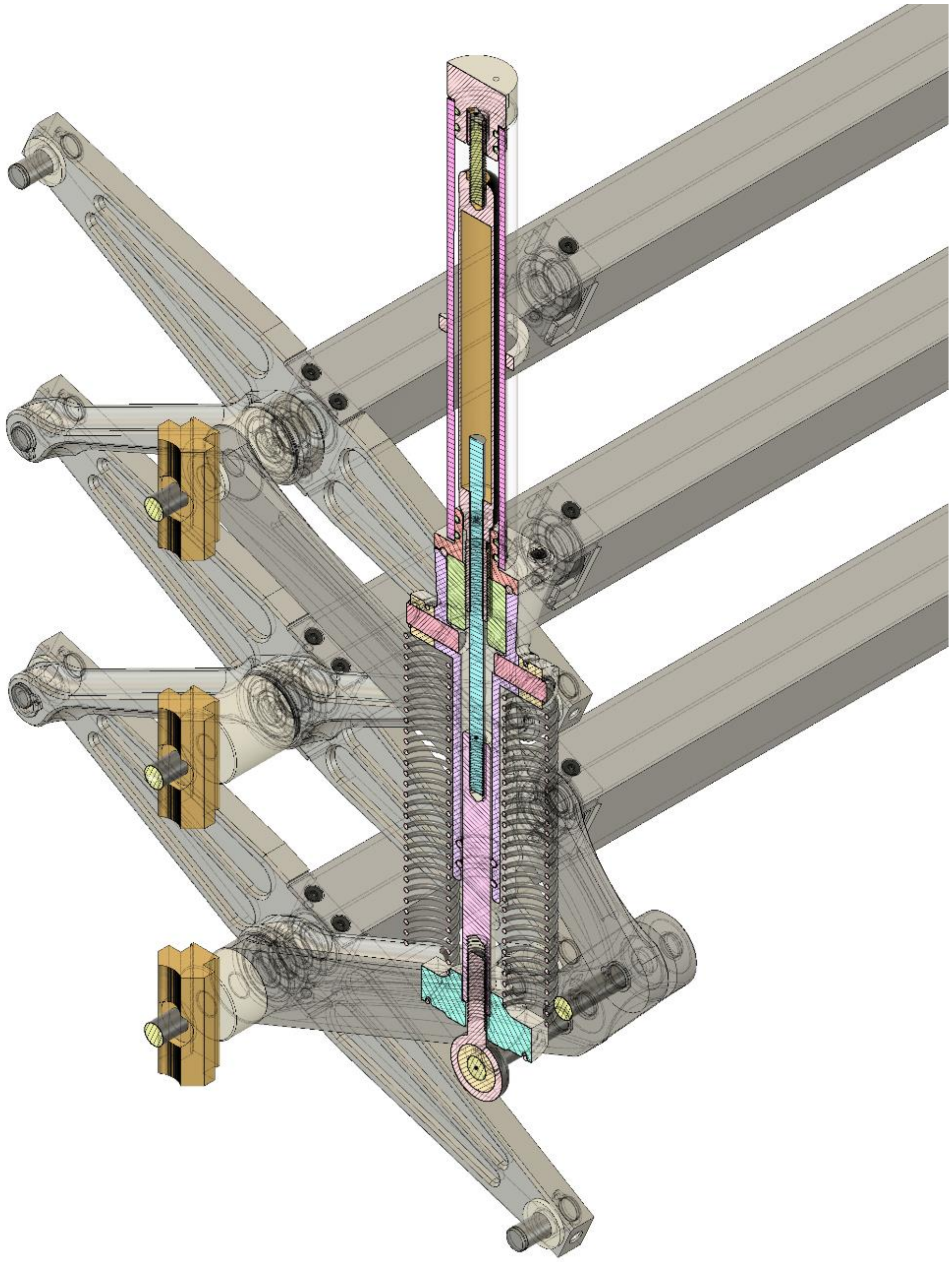


FIGURE 9: SECTION ANALYSIS THROUGH SCISSOR MECHANISM COMPONENTS (SUN-BLIND BLADES OMITTED FOR CLARITY)

Modelling tolerance in a workflow

In mechanical engineering there are well-established and widely adopted standards for representing and analyzing tolerances (ASME, 2020), these are supported by metrology techniques for inspection that provide quality control with “as-made” dimensions. From an inspection report each deviation from the “nominal” geometry in the CAD model can be evaluated against the allowable deviation specified in annotations to the dimensions on the component drawings for the fabricator to produce.

The three screen grabs in Figure 10 illustrate each of these steps for one component within the sun-blind mechanism (highlighted in red) using the “Manual inspection report” commands in the Manufacturing workspace of Fusion 360. During the prototyping stage, incorporating these steps within the workflow of each iteration was a virtuous circle because it gave feedback to the designer about the implications in time and effort during fabrication of tightening or relaxing each allowable deviation by comparing the results of the inspection report against the performance of the “as-made” component.

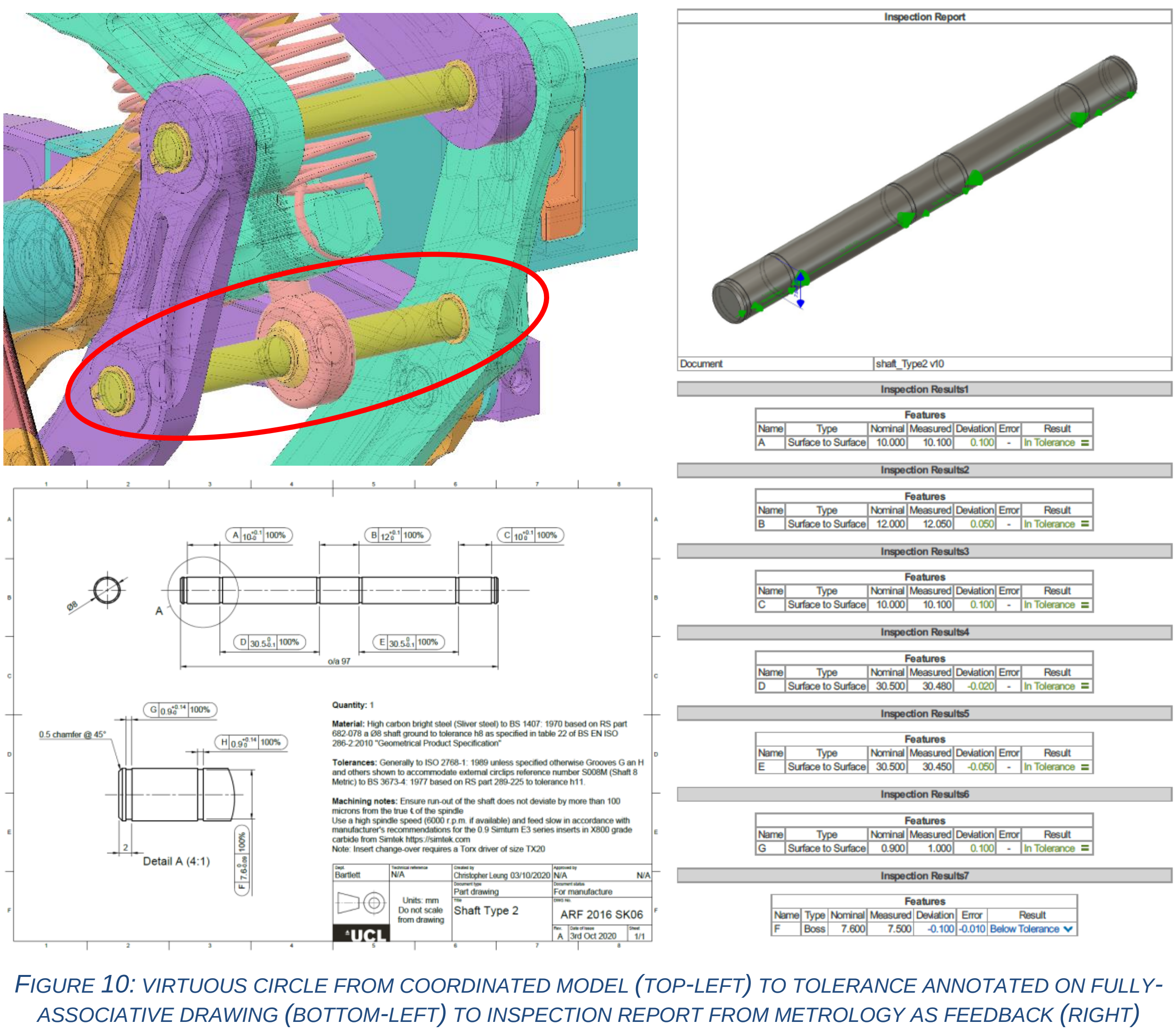


FIGURE 10: VIRTUOUS CIRCLE FROM COORDINATED MODEL (TOP-LEFT) TO TOLERANCE ANNOTATED ON FULLY-ASSOCIATIVE DRAWING (BOTTOM-LEFT) TO INSPECTION REPORT FROM METROLOGY AS FEEDBACK (RIGHT)

A conventional engineering approach might arguably only use the allowable deviations specified in relevant international standards and data from manufacturers, however, while these are also referenced in the component drawing (e.g. ISO 2768-1) the complementary value of the steps described here to a DfM education is to give the designer both software tools and a methodology for building up their experience to exercise critical judgement using evidence-based decision-making.

Within a mechanical engineering project the range of dimensional variation between components is generally of a similar order of magnitude, however, within a construction project the range of dimensional variation can be different by orders of magnitude. Consider the contrast between the low-tolerance centres of in-situ cast concrete columns with those of high-tolerance extruded aluminium cladding mullions and glazing units (BS, 1990). Similarly, construction has allowable deviations guided by relevant national standards (BS, 1988) and specified with reference to manufacturers and industry associations (Ballast, 2007).

Given these differences, the benefit of teaching the modelling of tolerance within an iterative workflow is that the results of comparison between the as-built dimensional variation and the "nominal" CAD representation have value because it informs the *actual* tolerances required of fabrication. This can then be considered against the implications in time and cost of achieving those tolerances.

Observing that it is common practice in industrialized manufacturing to design test-points into a product for quality control, adopting "Design for Metrology" into the components for constructing buildings can serve the same function, providing a systematic quality control for the correct positioning during assembly as well as traceability of the component back to its fabrication. These considerations further encourage a "model-make-measure" approach to educating DfM.

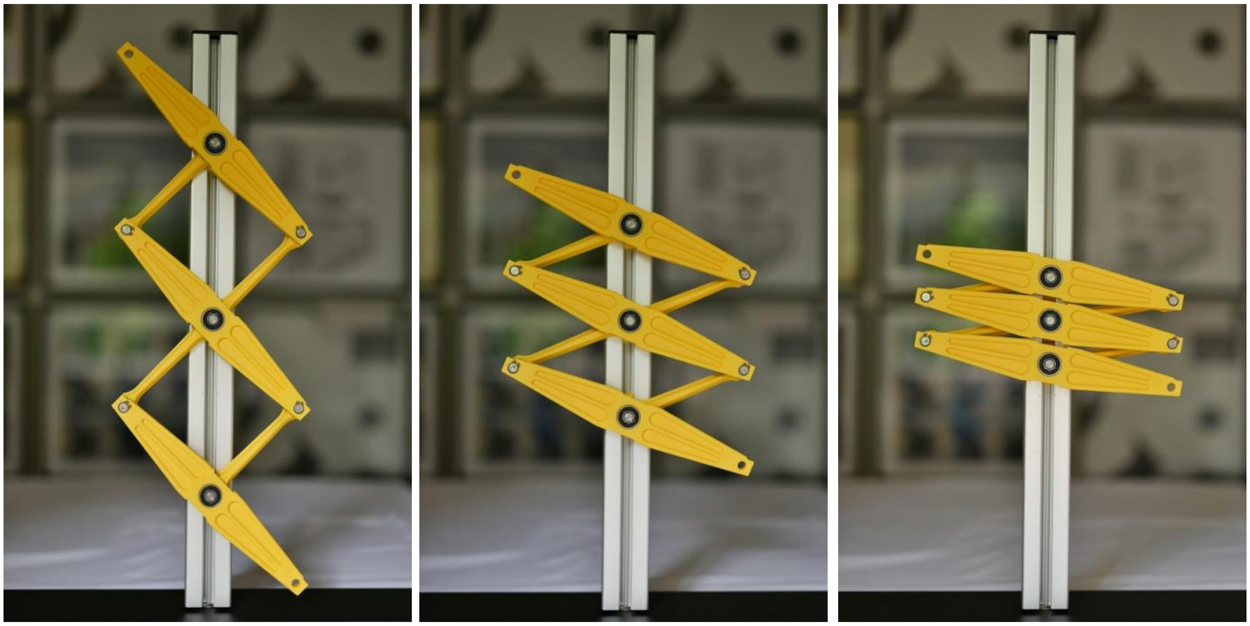


FIGURE 11: PROTOTYPE OF SCISSOR MECHANISM FOR TESTING

Benefits of the component-based approach

Adopting a component-based approach to modelling in which components are linked into assemblies and where it is necessary (or convenient) nested as sub-assemblies allowed this project to exploit the fully-associative links in Fusion 360 between design file(s) and drawings. Once COTS (Commercial Off The Shelf) components were given their supplier code and bespoke components such as 3D prints assigned a part number, together with specifying the correct physical material, a comprehensive BOM (Bill Of Materials) as well as exploded component drawings to guide assembly where generated as shown in Figure 14.

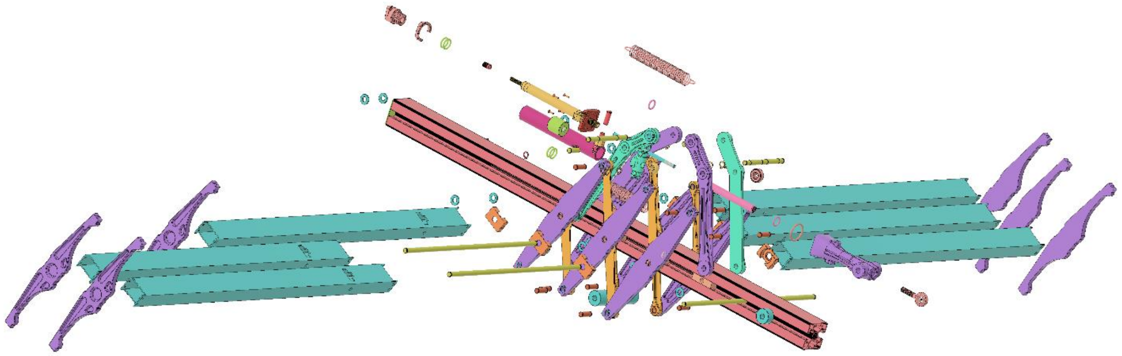


FIGURE 12: COLOR CYCLING FOR MANAGING HYBRID MODELLING OF IN-FILE AND LINKED COMPONENTS

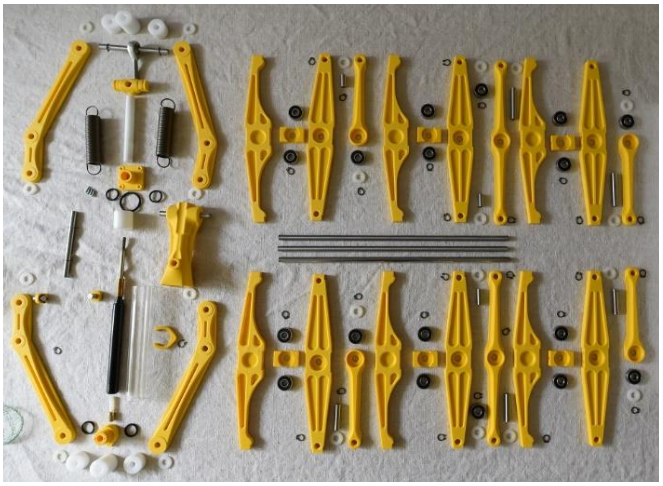


FIGURE 13: PROJECT AS A KIT-OF-PARTS READY FOR ASSEMBLY

It is hard to over-state the value of these documents to the evolution of a project from a draft design to the status of "For Manufacture" if the quality of information can be raise high enough to be used intelligently as metrics in DfM decision-making. The example shown in Figure 14 of an exploded assembly drawing generated from the Animation Workspace provided a stimulating prompt to consider and discuss how to plan the sequence of assembly and disassembly. It illustrates and enumerates which components have requirements for tool access prompting consideration about tool clearance, access for the seating of rubber seals as well as the application of retaining compounds, sealants and lubricants.

Fusion 360’s documentation features could be adapted as *kaban* cards given that the component inventory at the sub-assembly and assembly level shows the number of instances and stock code/part number. The total mass of components (in kg) can be calculated by extracting the BOM from Fusion 360 as a *.csv file and applied as a Quality Assurance Procedure (QAP) for inventory completeness prior to assembly using an electronic balance to obtain a checksum, as used by a leading Swedish OEM the author visited preparing for this talk.

Parts List

Item	Qty	Part Number	Description	Material	Mass
1	1	CouplerPin	M6x30mm stud w/full thread	Nylon 6/6	0.7481 g
2	1	Schott Boro 3.3	Enclosure	Glass	73.452 g
3	1	StrokeAdapter	Thermally insulating connector	Acetal Resin, White	13.747 g
4	1	ActuatorOrbesenSmall			55.2168 g
4.1	1	StrokeRod	Piston	Stainless Steel	28.2619 g
4.2	1	CylinderBody	Wax cylinder	Aluminum	26.955 g
5	1	EndCap	Cap seal & wire guide	Acetal Resin, White	12.3309 g
6	4	RS 705-8958	'O' ring 14x2.5mm	Rubber, Nitrile	0.3053 g
7	1	RS 278-578	M6 x 13.5mm insert	Brass	2.7418 g
8	1	Turned part	Collar actuator holder	Acetal Resin, White	15.098 g
9	4	RS 179-5676	ISO7046-1 - M2.5x10-4.8-Z-ISO	Steel	0.4306 g
10	2	Turned part	Spring pins		3.3321 g
10.1	1	RS 280-521	M8 washer to DIN 34815	Nylon 6/6	0.3262 g
11	1	FrontCap	Custom 3D print	ABS Plastic	7.579 g
12	1	RS 705-8958	'O' ring ID25x3mm	Rubber, Nitrile	0.7461 g
13	2	RS 705-8958	'O' ring ID12x2.5mm	Rubber, Nitrile	0.2683 g
14	1	3D print	Collar assembly		61.2703 g
14.1	1	3D print	Collar		0.00 g
14.1.1	1	SpringBush v8			0.00 g
14.1.1.1	1	3D print	Spring Bush		0.00 g
14.2	1	3D print	Spring Bush	ABS Plastic	61.2703 g
14.2.1	1	3D print	Spring Bush	ABS Plastic	61.2703 g
15	1	MB-M08			34.7724 g
15.1	1	POS 8.EU	Rod end M8x1.25	Steel	23.3728 g
15.2	1	POS 8.EU	Ball Dia 8mm	Bronze	11.3995 g
16	2	Springmaster T32280	Extension spring OD 20x100x1.8mm	Steel	35.8772 g
17	10	RS 289-225	S008M circlip to BS3673	Steel, Carbon	0.2634 g
18	1	Turned from RS682-078	Shaft Type2 to BS1407	Steel	38.0196 g
19	2	Turned from RS682-078	Shaft Type 4 to BS1407	Steel	9.3881 g
20	2	SpringBush		ABS Plastic	1.4107 g
20.1	1	3D print	SpringBush	ABS Plastic	1.4107 g
21	1	SpringTBush		ABS Plastic	10.1786 g
21.1	1	SpringBush v8		ABS Plastic	10.1786 g
21.1.1	1	3D print	SpringTBush	ABS Plastic	10.1786 g
22	1	3D print	Sensor cable tidy	ABS Plastic	1.4256 g

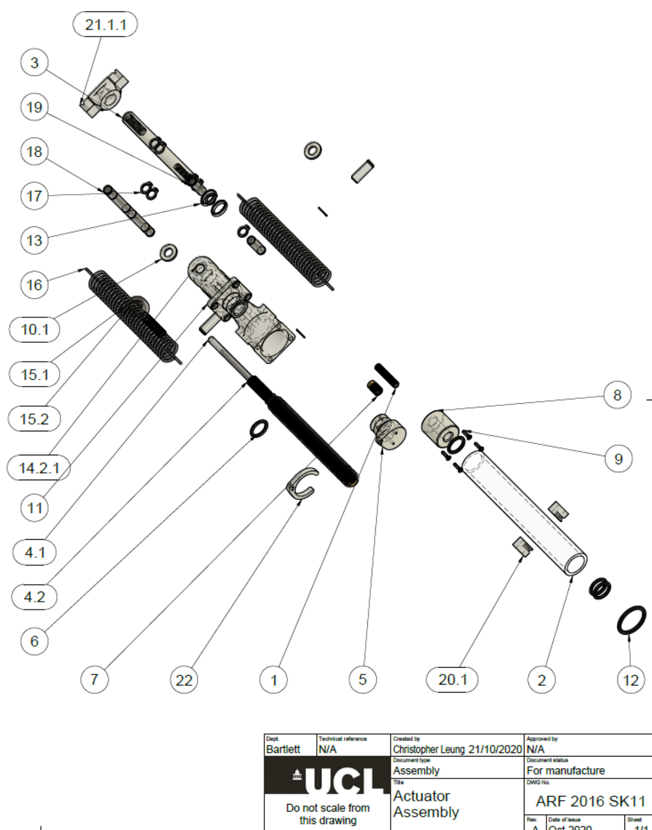


FIGURE 14: BILL OF MATERIALS (BOM) EXTRACTED FROM THE DESIGN FILE AND EXPLODED ASSEMBLY WITH PART REFERENCING CREATED USING THE ANIMATION WORKSPACE

Whilst it is stating the obvious, it must be pointed out that the value of features such as BOM and assembly drawing generation is in direct proportion to the quality of the referencing used to create them. While Fusion 360 provides an excellent software framework, its effectiveness in practice is determined by a progressive culture of adoption and the human factors of usage. A Model-Make-Measure approach to teaching DfM attempts to illustrate the benefits of linking between the quality of information and the fabricated outcome by example.

The relative ease with which these documents can be continuously generated as a project develops is valuable when used as a source for critically evaluating the design to consider strategies for part rationalization and the simplification of assembly and manufacturing steps in a bid to reduce time, cost, complexity and margin of error.

Collaboration with Fusion Team

UCL is a global university that attracts students from around the world, the Design for Manufacture course is fortunate to enjoy the attendance of a truly international community of students and staff that hail from twenty-seven different countries across four continents.

During the global COVID-19 virus pandemic, the delivery of teaching has transitioned from “face-to-face” to “remotely-accessed” tutorials, this change in delivering teaching together with the wide geographic distribution of students from each other has challenged educators and students alike to communicate effectively on-line to exchange geometry and project meta-data. This next case-study is a project by a group of seven students who have been separated by geography but have united their efforts behind a common model with a fabricated outcome.

Adopting the distributed modelling approach

This student project responded to a brief for an enclosure with a speculative proposal for an “Inhabitable Camera Obscura” as shown in Figure 15. While the forms of its components and the surfaces of the enclosure were created and developed using a range of software tools, they were brought together by creating a project to share the data in Autodesk’s cloud-based Fusion Team platform.

The virtue of the distributed modelling approach is that responsibility for the design and development of each component can be divided among the students, with the equity and fairness of the division of labour negotiated with the project tutors. Meanwhile, a coordinated model can be developed that brings all those components together at a selectable version number and then specifies their relationship to one another. In many ways defining the relationship between component in the coordinated model shown in Figure 15 can provide the basis for negotiating the resolution of each component’s design.

Similar to the previous case-study, the judicious use of the Joint Origin command to specify the 3D location of each coordination point and its associated plane for each component provides the terms of engagement for negotiating not only component-to-component positioning but also accommodating the direction and magnitude of tolerance due to the dimensional variation in material, fabrication process and assembly method.

Working though the definition of these components relationships also supports planning the assembly and disassembly by highlighting where there are access requirements and the need to provide tool clearances. For this exercise, investing time early in the project to model the tools, tool holders and standard fasteners in a library file that is shared in the asset folder on Fusion Team can pay dividents.

A special thanks to Doris Fisher at Autodesk for her advice and sharing her experiences with us of supporting other Universities across Europe while we developed our use of Fusion Team on student projects.

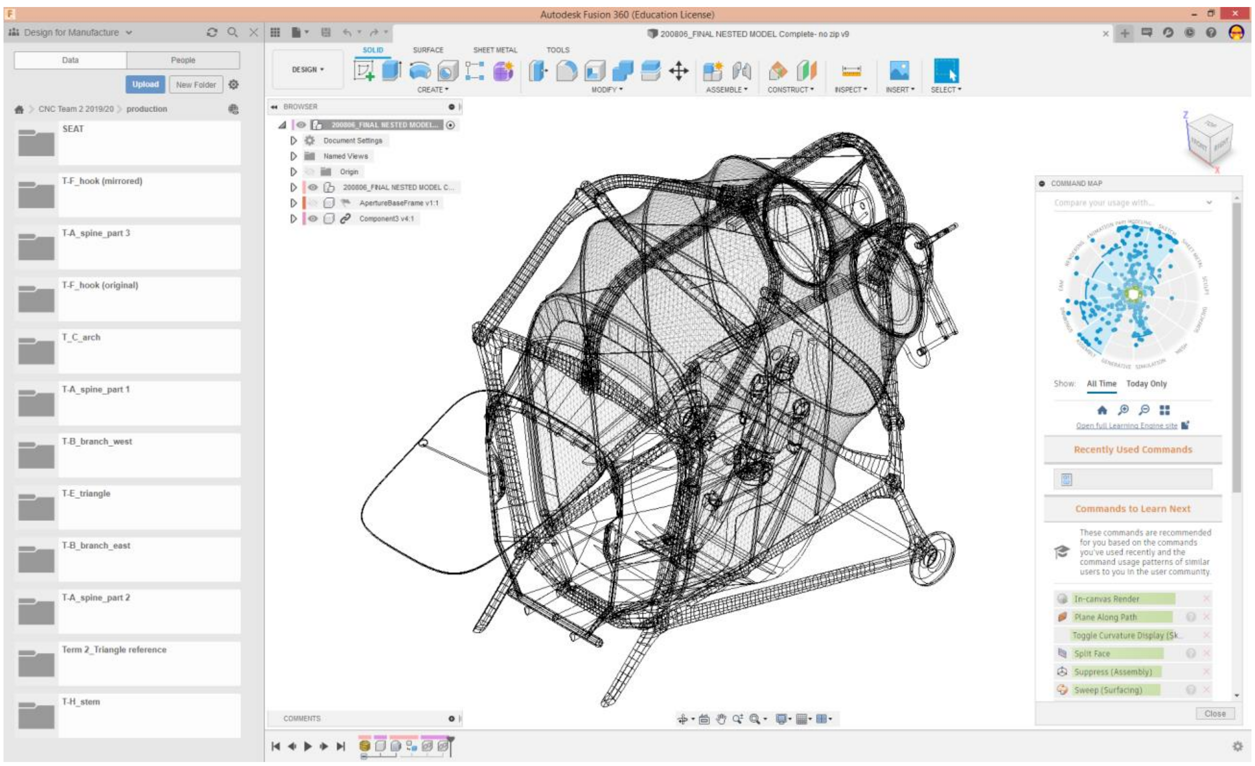


FIGURE 15: THE "INHABITABLE CAMERA OBSCURA" PROJECT SHOWING THE CONSOLIDATED ASSEMBLY (SCREEN CAPTURE OF FUSION 360 MODEL VIEW SHARED IN FUSION TEAM)

Organising and generating manufacturing data

Using the distributed modelling approach, each component linked to the coordinating assembly file was moved into a dedicated folder as shown in the datapane on the left-hand side of the screen grab in Figure 15. This organization means that the manufacturing information is generated in the manufacturing workspace of each component file which is in the custody of the student(s) responsible for the design and development of that component.

This folder structure also served to divide the project into approximately a dozen work-packages to distribute generating the necessary manufacturing information. As students could generate this individually in the manufacturing workspace for their component, the duration of machining time could be estimated using the toolpath simulation commands. This had the advantage of managing the scheduling of access to the workshop to make best use of the available machining capacity by sharing this information across all the components in the project.

Managing the machining schedule of a dozen work-packages has shown the significance of factoring in a reasonable allowance for the set-up and take-down time between cycles. As every commercial production workshop knows, this is non-trivial as the work-holding requirement can vary significantly from component-to-component, with an example shown in Figure 16. We did briefly experiment with using Autodesk Fusion Production and would like to develop its implementation further to support this stage in project work at a future date.

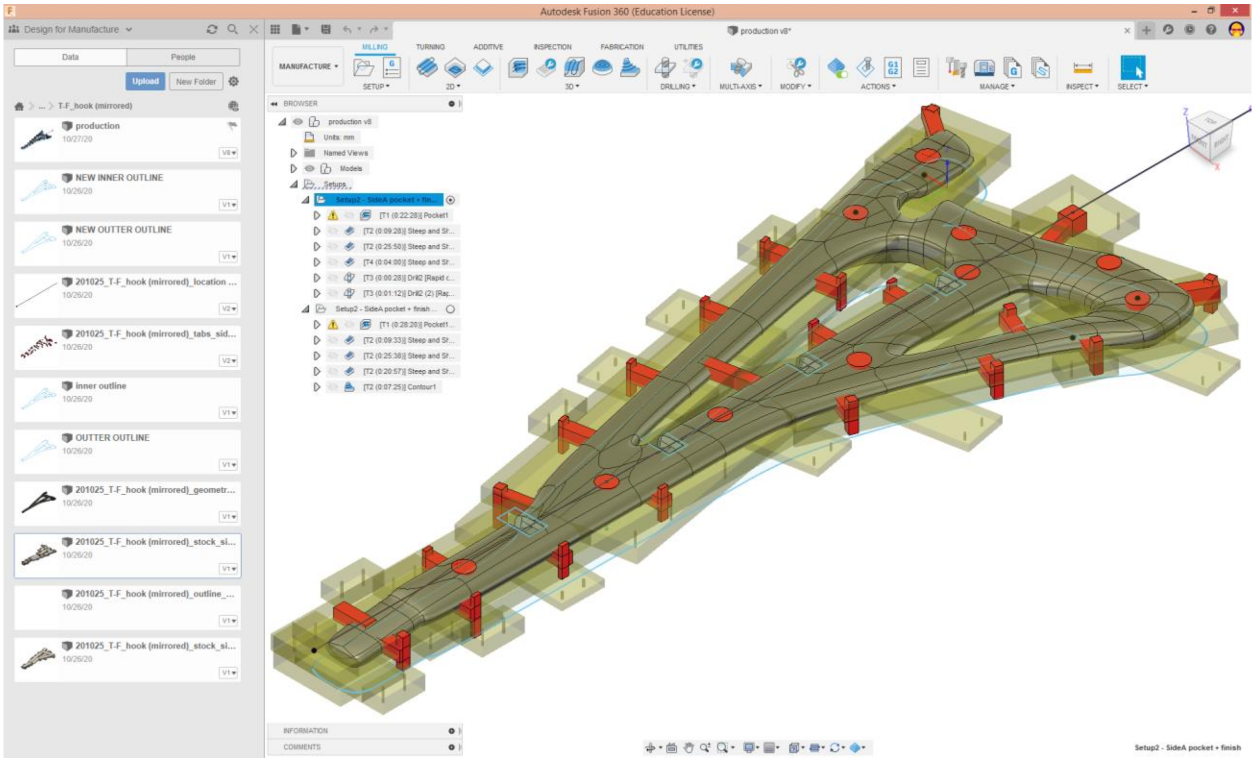


FIGURE 16: TOOLPATH PLANNING AND WORKPIECE HOLDING STRATEGIES FOR 3D MILLING THE TIMBER FRAMES (SCREEN CAPTURE OF THE MANUFACTURING WORKSPACE IN FUSION 360)

This project illustrates the challenges of meaningfully representing dimensional coordination between components given their freeform geometry, especially given that timber is an orthotropic material with deviation in axial, longitudinal and radial axes from stress and strain under load.

Once the components start to be fabricated as shown in Figure 17 the locations for attaching registration markers for inspection metrology can be considered while giving consideration to maintaining a line-of-sight to those locations for as long as necessary during the assembly process. This could be done using photogrammetry, LiDAR scanning or EDM with a total station or permutations of all three once the registration points are defined.

FIGURE 17: STRUCTURAL FRAME SUB-ASSEMBLY 3D CNC MILLED GLUE-LAMINATED TIMBER (IMAGE COURTESY OF WILLIAM-VICTOR CAMILLERI)

The transfer of skills and methodologies to industry

An example of student work that embodied the complete Model-Make-Measure approach was authored by Matthew Ferguson, "Sloppy topologies – Precise Datums" shown in Figure 18 hydroformed sheets of Grade 304 stainless steel with a 2R bright annealed finish against modular CNC milled fixturing blocks. The dimensional variation in the surface formed by this inherently uncertain fabrication process was subsequently inspected by high-resolution 3D scanning with structured light and then imported back into the design representation.

Rather than treat deviations from the "as-designed" as flaws, this project addressed uncertainty as an opportunity through the bespoke design of a grid of CNC machined compensators that superimposed a precise grid of datums onto the project.

The practical execution of this project raised interesting questions about matching the capture of "as-built" geometry data with the ability to act on it through the means of fabrication that is available. Flawlessly transferring registration points from a scanning site into a machining cell is non-trivial when thin materials suffer distortion from their fixturing. Where and when in a fabrication workflow to apply inspection to a workspiece as it moves from process to process deserves carefully planning to match the means of measurement to the means of making.

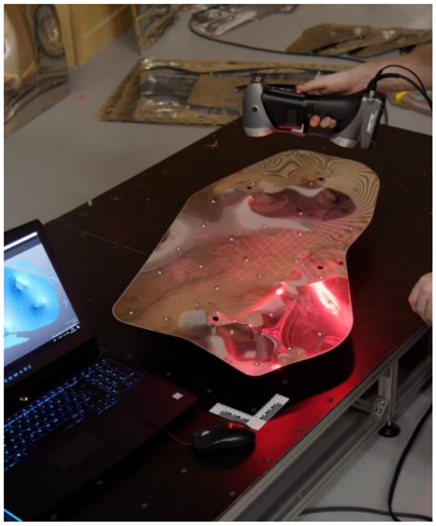


FIGURE 18: "SLOPPY TOPOLOGIES AND PRECISE DATUMS"
(TOP RIGHT IMAGE COURTESY OF MATTHEW FERGUSON)

The skills gained and the methodologies adopted through a model-make-measure approach to DfM can be shown to have relevance to improving the practice of delivering projects.
As an Alumni of the DfM course, Matthew Ferguson was employed by the design for manufacture business Cake Industries Ltd who specialize in the fabrication of bespoke staircases. As a progressive business they found an immediate application of his skills to tackle projects involving the uncertainty of fabricating construction for existing building.

By deploying LiDAR laser scanning on-site and incorporating the "as-built" data-set into their digital workflow they identified unexpected physical clashes aswell as useful quirks in the existing building that they used to inform their design and fabrication information as shown in Figure 19. This saved them time, cost and reduced their exposure to the risks and liability of rework and delay, those very same deficits in the performance of the construction industry that motivated the adoption of a model-make-measure approach to DfM education.

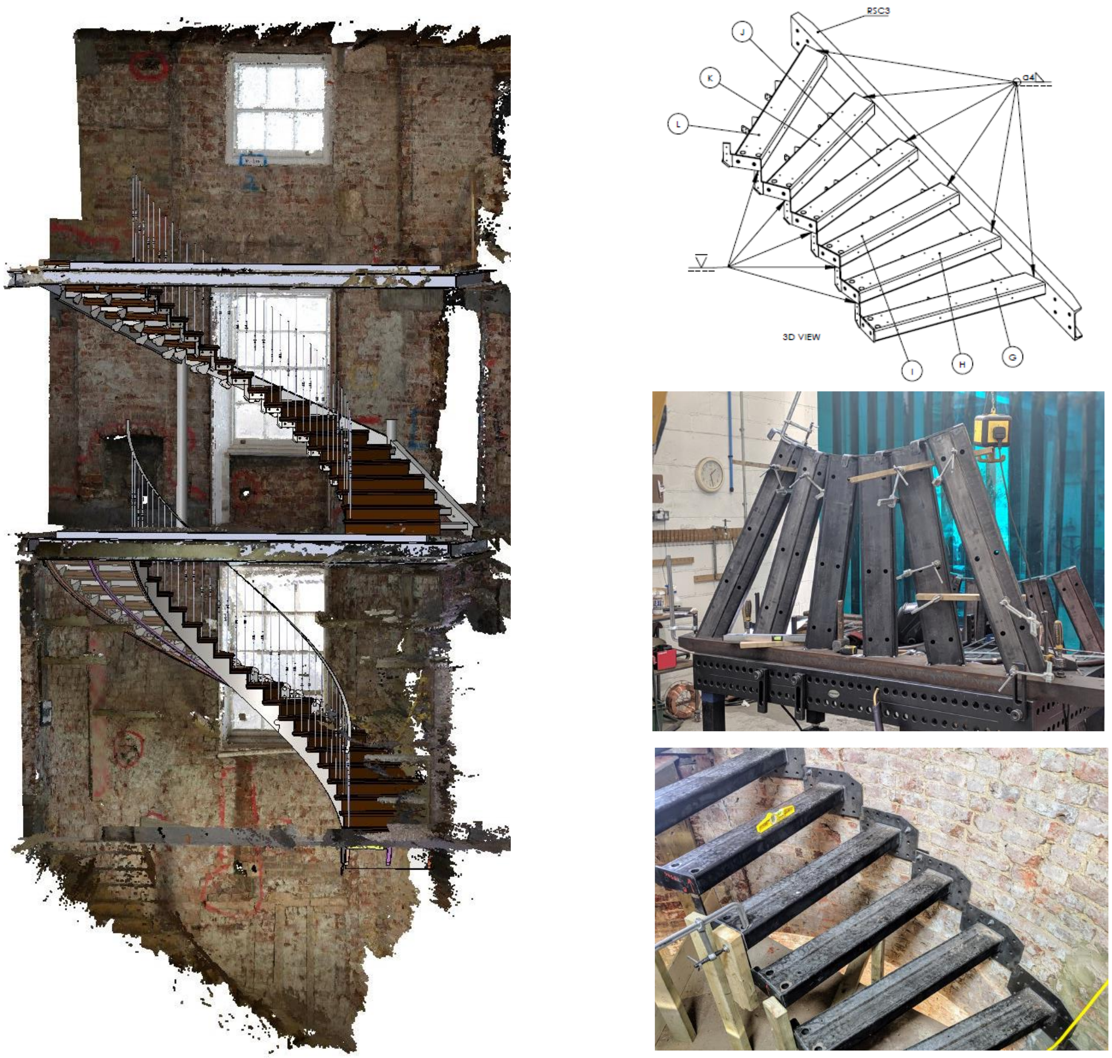


FIGURE 19: MODEL MAKE AND MEASURE IN PRACTICE
(IMAGES COURTESY OF CAKE INDUSTRIES LTD AND MATTHEW FERGUSON)

Moving from bespoke staircases to bespoke homes, Matthew Ferguson was subsequently employed by the award-winning design and manufacturing company Facit Homes founded by Bruce Bell in 2007. Facit homes specializes in building houses from a proprietary system of modules that Facit manufactures off-site using digital work-flows to manage the build process from BIM model through production drawings to digital fabrication process and site installation.

Facit homes represent a business model of linking the design intent to the built outcome and taking control of the process from start to finish. In an established organization with existing digital workflows, the model-make-measure mindset added to the systematic continuous improvement of processes from the habit of gathering, recording and analyzing lessons-learned.

The last iteration of a project provides decision-making value within terms of reference that are shared with the current project and could give predictive valve when anticipated to be relevant to the next project.

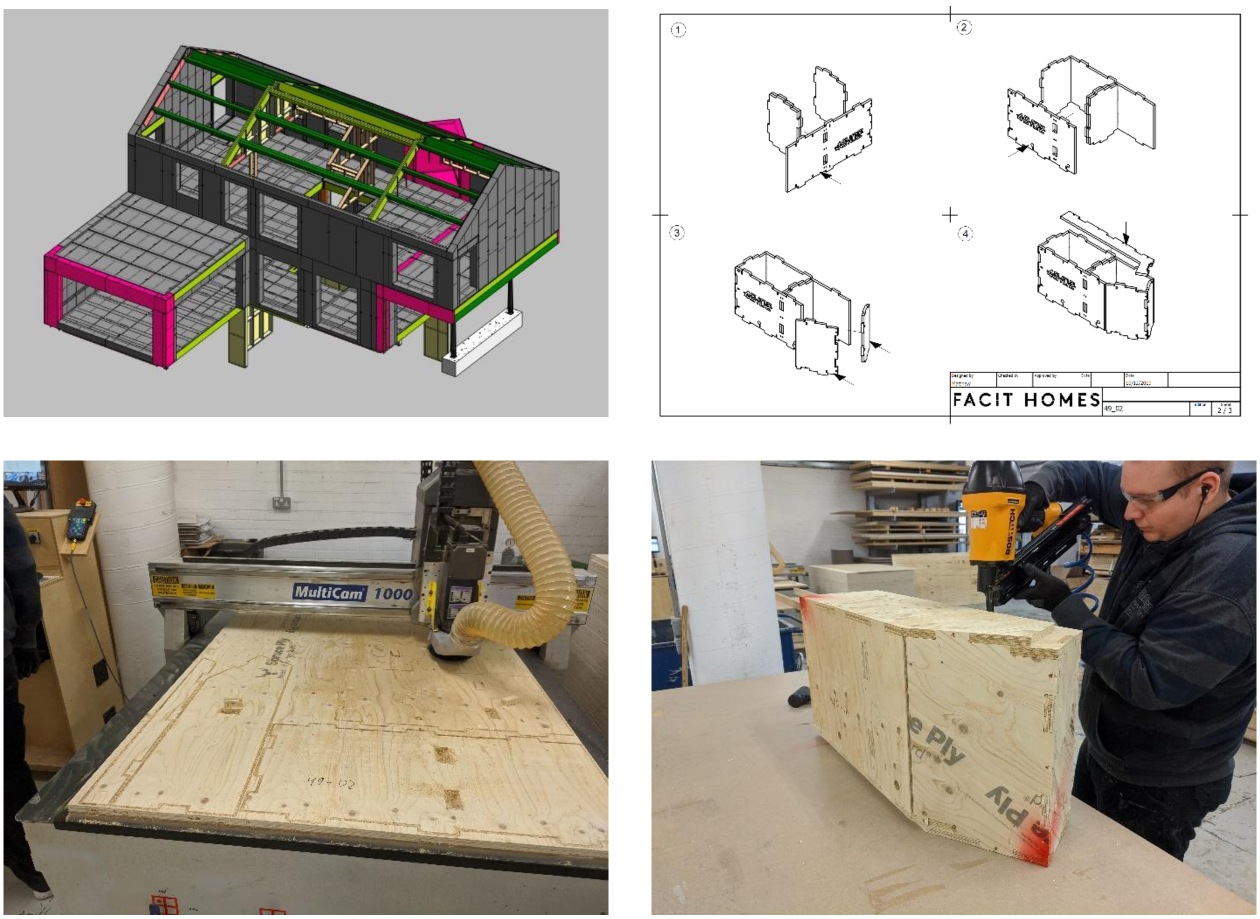


FIGURE 20: OFF-SITE MANUFACTURE OF PROPRIETARY MODULES FOR BESPOKE HOUSING (IMAGES COURTESY OF FACIT HOMES LTD)

Conclusions

The “Model-Make-Measure” approach aimed to instill in students a close-coupling between the digital representation of their design intent with the implications that constraints in the material properties, fabrication processes and assembly sequencing has on the success of their project.

The feedback that students gain from the close-coupling of “nominal” design intent with its “actual” fabrication outcome through measurement aimed to foster a fundamental understanding of the dimensional variability of fabrication, the concept of tolerancing. In addition, to learn techniques for the appropriate represention of tolerance, to analyse the implications of its variability and gain practical experience of how compensating for its effects is a logical part of project development.

Our adoption of Autodesk Fusion 360 in teaching Design for Manufacture has provided a pathway from component design to CNC fabrication through its CAM manufacturing workspace and its support for post-processors that match the range of NC machinery available to our students. As an end-to-end software tool it has enabled design and fabrication data to flow freely around the “Model-Make-Measure” feedback loop, as we hope has been demonstrated by accomplished student and staff users in the projects presented.

It must be acknowledged that the capabilities Fusion 360 affords a user exists within a wider ecosystem of software tools that are available to Design for Manufacture students and practitioner staff. The need to exercise critical judgement in the benefits gained to their workflow from the capabilities of any given software tool has to be balanced with the difficulty of acquiring and maintaining the level of proficiency necessary to realise those benefits.

As with any investment that stakes the risk of time and effort versus a reward of improvement and advancement we have found that this balance is difficult to strike. On the one hand the time available to teach skills on a masters course is finite, on the other the opportunities to usefully apply the benefit of its capabilities in projectwork is dependent on many variables that differ with every individual student. In this regard, we hope that the projects presented in this industry talk demonstrate the relative ease with which we found Fusion 360 can be introduced and learned in a 15-month masters course.

In addition, we have shown that graduates from this academic programme have found employment in specialist design for manufacture companies and have applied lessons learned from a “Model-Make-Measure” approach directly to the challenges of the construction industry. This goes some way to answering the call from industry for a new generation of designers who are also makers to deploy the skills needed to practice at the challenging interface between design studio and the point of industrial production for the improvement of our built environment.

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