Influence of Stakeholders on Industrial Design Materials and Manufacturing Selection

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Surprisingly little is reported on the pragmatic influence of project stakeholders on industrial designers' selection of product materials and manufacturing processes. This paper reports on a descriptive scoping study that revealed these influences as critical in making effective selection decisions. Using interview and case study methods, the study elicited the professional practices of industrial designers. These are analysed in the paper, leading to the formation of a four-way stakeholder description of materials and manufacturing selection in industrial design, spanning: users, clients, manufacturers/vendors and designers/design team members. The practical influence of each stakeholder on materials and manufacturing decisions is discussed. With clients excepted, under most circumstances the flow of activity is initially from designer-to-stakeholder, rather than stakeholder-to-designer. Crucially, the paper establishes creativity in the selection of product materials and manufacturing processes as cleverly attending to stakeholder influences, and distinctly not to unconstrained freethinking or self-centred decision-making. The paper reviews professional boundaries of responsibility and approach to materials and manufacturing, identifying industrial design as a fusion of designer-maker and design engineer perspectives. Industrial designers commonly view materials as a contribution to a product's user interface, with an associated effect on users' experiences of product utility and supra-functionality.

***Keywords* –** Industrial Design, Materials Selection, Manufacturing, Decision-Making, Education.

***Relevance to Design Practice* –** Elicitation of design practices is important on two accounts: (1) for directing revisions to educational and professional training initiatives to ensure relevance and timeliness, and (2) for helping managers to lever maximum contributions from their design staff.

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Introduction

Materials and manufacturing processes are vital in the creation of a new product. They are the physical stuff of products; the means by which design concepts are materialised and transformed from the world of the computer model to the physical world. Material selection significantly influences the form, function and perception of a product (Doordan, 2003). Material and process combinations directly affect people's interactions with products and the experiences that ensue (Karana, Hekkert, & Kandachar, 2009; Rognoli & Levi, 2005; Zuo, Hope, Jones, & Castle, 2004).

Given the indisputable importance of materials and manufacturing, the practical factors driving industrial designers' decision-making in the area remain poorly understood. Although many excellent sources are available to build a personal knowledge of materials and manufacturing processes (Lefteri, 2006, 2007; Thompson, 2007; Beylerian, Dent, & Moryadas, 2005; Swift & Booker, 2003; Lesko, 1999), few methodological sources address the issues involved in putting this knowledge into practice. The most significant works here are provided by Ashby and Johnson (2002), who fuse developments in engineering materials selection software (i.e. CES Selector, http://www.grantadesign.com/products/ces) with a product-oriented perspective on materials selection, and van Kesteren (2008), who focuses on product designers' materials information needs. Occasionally, case studies of product design projects, such as those by Campos (2006) and Cullen and Haller (2004), provide some insights into materials and manufacturing rationale, but such sources omit cross-comparisons between design practices and do not seek to develop theory or models of practice.

Most striking is the lack of exposure given to influences from project stakeholders. Industrial design involves associations with project clients, manufacturers, vendors, users and design teams. No reputable industrial designer works in isolation, so it is reasonable to presume that each of these stakeholders exercises some influence over the selection of product materials and manufacturing processes. The research reported in this paper aimed to uncover, structure, and report stakeholder influences to construct a framework describing the practical circumstances in which industrial designers' take materials and manufacturing decisions.

The outcomes of the research were foreseen as being principally important for strengthening the methodological foundation, content and delivery of materials and manufacturing training within industrial design degree programs. Historically, finding the right balance for such training has been a struggle

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(Myerson, 1991) because industrial design is situated between two quite different but adjacent professions, both of which are concerned with designing and making things: the professions of design engineers and designer-makers (Black, 1964). The former profession is strongly technical in nature and mathematical in its approach, while the latter is predominantly 'hands on' and vocational. In the context of new product development (NPD), design engineers are largely responsible for conceiving and realising mechanical and electronic systems within products, but their work also includes defining the engineering details of a design proposal so that it is suitable for tooling and production. Designer-makers are artisans or craftspeople who make a living from designing and making useful objects in specialist materials of their choice. Examples are silversmiths (e.g. jewellery, cutlery), ceramicists (e.g. kitchenware, tableware) and woodworkers (e.g. furniture, musical instruments).

The research identified as an important issue the extent to which design engineers' and designer-makers' distinct approaches to materials and manufacturing selection are retained in industrial design practice, thus helping to establish the right pitch of content and delivery for student training. Given that design engineers and industrial designers typically work side by side in product design teams, the research also provided an opportunity to explore boundaries of professional responsibility for the subject, highlighting design management issues.

Industrial Design as a Specialty

It is helpful to begin with a brief account of industrial designers' general responsibilities within the business of product design, so that materials and manufacturing can be placed into an occupational context.

Industrial designers are employed at the 'front-end' of NPD, generating visions, concepts and proposals that fulfil peoples' needs and aspirations for new products. They possess an overriding concern for human factors and endeavour to make new products especially attractive to people through a combination of fitness for purpose and appeal to the senses. Product attraction is directly attributable to people's interactions and progressive experiences with a product, spanning aesthetic experience, experience of meaning, and emotional experience (Desmet & Hekkert, 2007). It is therefore no surprise that user-centred design approaches are regarded as fundamental for successful industrial design (Green & Jordan, 1999).

Research studies describing industrial designers' priorities for product specification commonly take a dualistic approach that combines product utility (e.g. practical usefulness, performance, comfort) with product character (e.g. personality, style, soul, spirit). Researchers use various terminologies to refer to this duality, including practical/aesthetic (Heufler, 2004), functional/affective (Khalid & Helander, 2004), and functional/supra-functional (McDonagh-Philp & Lebbon, 2000). This study adopts the terms 'utility' and 'supra-functionality' in underscoring industrial design's involvement in the creation of products that both embrace and transcend utility. The two terms also avoid the awkward separation of utility and aesthetics, which is indivisible for many products (e.g. consider the aesthetic experience of squeezing a lemon using a juicer, or of taking time out to relax on a sofa).

Of course, although the division between functionality and supra-functionality is useful for academic deconstruction and theorising designs and designing, on a practical level it is artificial and counter to a designer's fundamental objective of synthesising form and function into a coherent whole. For example, a translucent polymer casing in an electric kettle allows users to view the water level (functionality), but also may convey a 'contemporary' personality through its frosted appearance (supra-functionality).

Research Methodology

The two gaps identified in the literature—stakeholder influences and legacies from adjacent design disciplines—were used to construct three principal research questions. The study sought to determine the pragmatic impact that stakeholders have on industrial designers' choices of product materials and manufacturing processes (RQ1, RQ2) and then to uncover crossovers of responsibility and approach between different design professions (RQ3).

- RQ1. What influences do stakeholders (clients, manufacturers/vendors, users, designers themselves) have on the selection of materials and processes in industrial design?
- RQ2. How are stakeholder influences taken into account and managed?
- RQ3. What crossovers exist between industrial designers', design engineers' and designer-makers' involvement in materials and processes?

Figure 1 illustrates the structure of the study, which may be broadly characterised as a descriptive study into, for and partially through design practice. Emphasis was placed on eliciting insightful descriptions from a small number of cases, rather than broad descriptions from a large number of cases. Because the research topic was unexplored, the priority was initial definition and understanding of the topic dimensions and dynamics, which could then lead to survey-based studies to validate the results against general practices (Eisenhardt, 1989).

The study involved two complementary strands of investigation, carried out in parallel. The first strand sought data of a typified nature on a general level. It involved interviews with designers to elicit their practices. The second strand sought data of a detailed nature on a documentary level, taking the form of a case study of a lengthy design project undertaken by the author. A diary of design activity was kept to document the project. Figure 1 shows the three phases of work used to elicit design practices. The first phase, on which this paper is based, analysed the pragmatic

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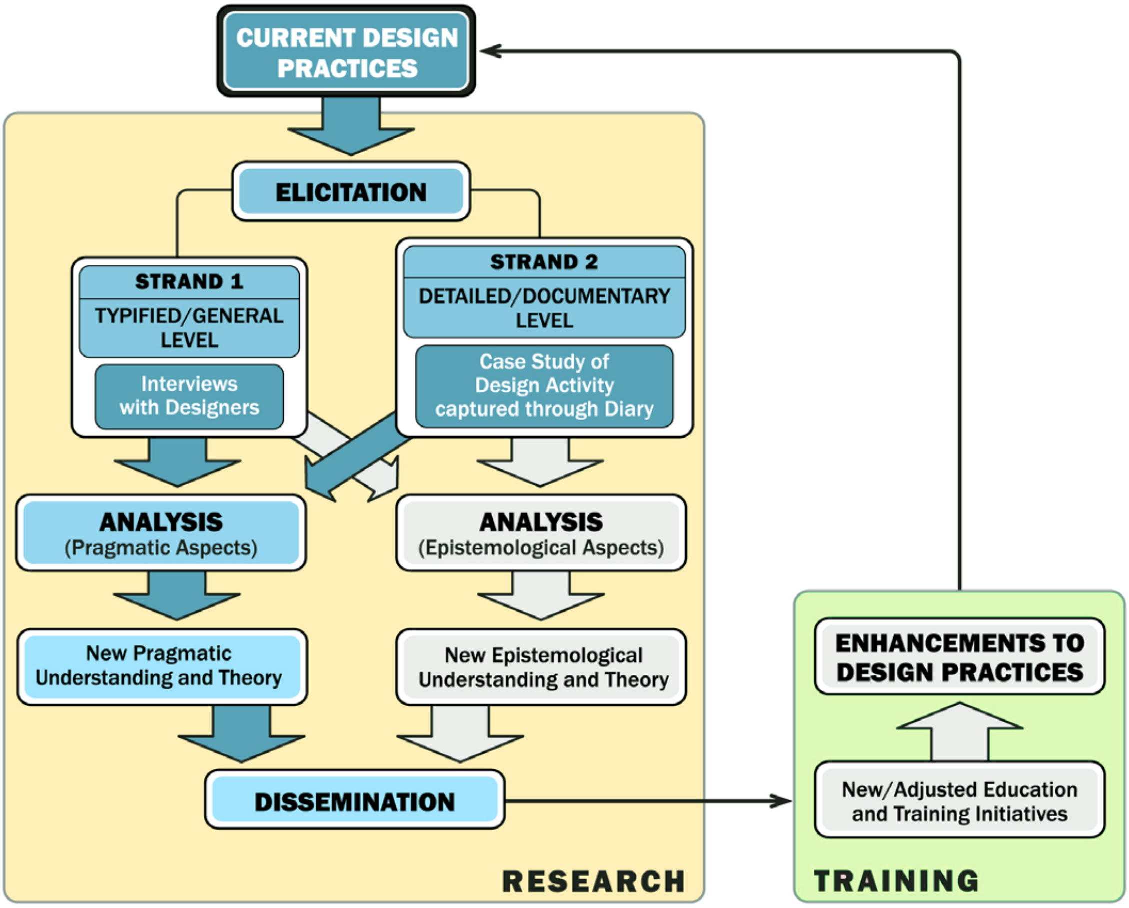

Figure 1. Structure of study showing cyclic relationship between design practice, research and training.

aspects of designers' materials and manufacturing selections. The second was an epistemological analysis, which looked at designers' knowledge, values, skills and information use in respect to selection activities. The third phase, for which preliminary results have been published (Pedgley & Norman, 2007), involved new initiatives for training industrial design students in materials and manufacturing.

Interviews with Designers

The interviews were conducted in two sets. The first involved industrial designers working in a variety of commercial contexts (for RQ1-3). The second involved a design engineer and a designer-maker, both based in academia, but with their own commercial practices (for RQ3).

Representatives of the three main commercial contexts for industrial design were approached for the first set of interviews (in-house designers at manufacturing companies, members of group design consultancies, freelance designers), so that a variety of perspectives could be gathered. It was known that attracting designers to participate would be difficult and that asking for participation beyond a half day would be unreasonable. Interviews were thus chosen as the most appropriate tool for data collection, requiring minimal time commitment from the participants. In all, nine UK-based interviewees were secured, spanning staff at Samsung, Kenwood Design Office, Flymo, Nokia (in-house designers at manufacturing companies); Pentagram, BIBdesign, greymatter, Johnson Haigh Rogers (members of group design consultancies); and Dartnall Design Associates (freelance designer). Nine interviewees is a small group (20% of the total number of designers approached), but answered the research questions at the intended review level. The second set of interviews involved a design engineer (the Director of Loughborough University's Engineering Design Institute) and a designer-maker (the Course Leader for the 3D Design (Ceramics) degree at Loughborough University).

A semi-structured interview technique was used in being quick and easy to administer while promoting discussion and interviewee-led responses. The interviews of up to two hours were conducted at the designers' premises and audio recorded by consent. Factual and attitudinal questions were posed, with interviewees citing either a specific brief/product or their typified experiences in the area. Products mentioned during the interviews were approached as tangible discussion points, thereby allaying fears over the honesty of responses. Table 1 lists the interview topics and sub-topics based on elaborations of RQ1-3 and with reference to a theoretical framework of knowledge, values, and skills, this being a good fit for analysing design decision-making (Norman, 1998).

Table 1. Interview topics, content analysis codes and example diary excerpts

Topics and sub-topics	Analysis code	Example diary text and [entry number]
Pragmatic: Uses of materials and processes within industrial design • Achieving product utility • Achieving product supra-functionality	Fn	"Here I was assessing the visual qualities of different combinations of coloured polymer in relation to the wooden (natural) neck that Rob will be building." [222]
Pragmatic: Constraints on choices of materials and manufacturing • Variations between briefs • Variety of materials • Scope for changes • Practical factors driving selection and direction • Impact on creativity	Cn	"Re-measured the bed of the router to see if its size will have implications for the CAD model I produce to subsequently send it for manufacture. It's 400mm x 400mm, so the guitar components will have to be routed in two halves, then joined together." [242]
Pragmatic: Level of detail reached • Cut-off points from ideation to production • Responsibilities in relation to colleagues	Lv	"It had been established some while back that I'd provide recommendations for a mass-manufacturing route, as a 'drawing the line' under my realistic active involvement in the project (in relation to both skills and time)… I've just formalised this by stating that it will be in the form of a written report." [275]
Epistemological: Use of information • Use of samples • Consultation with other sources • Role of computers in selection	In	"Working out how much epoxy resin I'll need… sent off a fax to John Burn (Birmingham), CIBA suppliers, for a quote." [304]
Epistemological: Knowledge and values • Different ways of knowing • Ways of keeping up-to-date • Experiential learning • Core subjects for industrial designers to know	Kn	"Have made a test sample of Lexan-Forex joint using the 3M polyester adhesive. Will wait for this to cure, and then compare its performance with that of the ITW acrylic adhesive." [199]
Epistemological: 2D Modelling • Thinking embedded in sketches • Communication of ideas	2D	"Quick summary of desired surface textures intended to be referred to at a design meeting to be held tomorrow." [228]
Epistemological: Cognitive modelling • Materialisation of ideas • Linking form ideas to industrial forming processes	Cg	"As I was walking into University I had a thought about how the soundhole might be produced – using a warmed male-female punch (this had crossed my mind in the light of some difficulties of creating a clean circular hole using a trepanning tool and jigsaws)." [105]
Epistemological: Tasks for deciding on materials and processes • Thinking strategies and activities • Typical deliverables	Ts	"Starting work now on a PDS, to start laying down design direction and technical features" [26]
Epistemological: Timing and sequence of attention • Priority as a subject • Phases of attention across projects	Wn	"Design work up until now has been fine, but I feel now that in order to progress, I need to know the particular material (i.e. plastic composites) more intimately – especially costs and manufacturing possibilities." [56]

Case Study of Design Activity

The author engaged in a long period of practice-based research to construct a case study that tracked the progress of design decision-making in a design project from brief to delivery of prototypes (Pedgley & Wormald, 2007). The case study was devised to provide answers to RQ1-3 through detailed and chronologically correct documentary evidence. Because the use of own design practices as a source of research data was unusual, rigorous methods for capturing and analysing own design activity had to be developed and evaluated.

The adopted data collection tool was a diary of designing. The tool's suitability was determined largely by considering what was practical to implement across a long (227-day) design project, and by determining a recording method that involved minimal processing and preparation prior to analysis. Diary entries were made at the end of each project day, giving an account of any attention paid to materials and manufacturing, and where relevant with direct reference to drawings, models and information sources. The completed diary of designing contained 312 entries giving a very personal account of involvement in materials and manufacturing; example entries are given in Table 1. A full methodological account of the diary has been published previously (Pedgley, 2007), discussing its design, testing and validity as a data collection tool.

The project chosen for the case study was the design of an acoustic guitar manufactured from polymers (plastics) rather than wood. This project was noteworthy on three accounts (Yin, 2003): it would represent a valuable innovation in the product sector, it would require design advice from varied sources, and its pursuance would fulfil personal interests as a musician. The project was carried out in an academic context with no commercial partners or imperatives. The brief identified five areas in which a successful polymer acoustic guitar could have impact.

Impact Area 1. Credible Alternative Material

The long-term viability of wood for guitar construction is uncertain because of over-forestation and unsustainable demand driven by Far East manufacturers. Alternative materials are needed to counter supply problems with traditional tone woods.

Impact Area 2. Reduced Manufacturing Cost

By using lower cost materials, specifying fewer parts (e.g. component consolidation) and using simpler construction (e.g. decreased manual labour), manufacturing costs and hence product retail prices can be lowered.

Impact Area 3. Improved Consistency

Wood is an inconsistent material requiring the skills of professional guitar makers to 'bring out the best' in any given timber. In mass production, it is not feasible for instruments to be individually customised. Instead they must be designed and manufactured to a standard construction, leading to undesirable material-based variance in sound quality in instruments. A shift to polymers, as nominally consistent materials, would plausibly lead to a reduction or elimination in sound quality variance in mass produced instruments.

Impact Area 4. Resistance to Environmental Changes

Wood is susceptible to dimensional distortions when subjected to changes in temperature and humidity, which can lead to physical cracks in instruments. Polymers have potential to circumvent this problem.

Impact Area 5. New Sensorial Possibilities

The use of polymers opens opportunities to create captivating instrument forms and finishes not possible with wood and not yet seen in the acoustic guitar market.

Given these product innovation points, it was clear that a successful design would rely on effective materials and manufacturing choices, especially in relation to sound, appearance and mechanical structure. The project was therefore well matched to the research questions. Furthermore, it was known that the ability of science and engineering to deliver practical advice on material selection and design for a polymer acoustic guitar was poor (Norman, 1993). Thus, the project would very likely reveal something about alternative *designerly* ways of knowing, learning about, and applying materials and manufacturing processes (Cross, 2006).

As a footnote, the design project was completed with considerable success and has now moved to a commercialisation phase under the name *Cool Acoustics* (http://www.coolacoustics.com), supplemented by significant events including the granting of a US utility patent (Pedgley, Armstrong, & Norman, 2005), a feature on the Discovery Channel (Ingram, 2006) and the recording of an album solely on a Cool Acoustics guitar (Giltrap, 2007).

Data Analysis Procedure

The analysis of the interview data commenced with verbatim transcriptions of the audio recordings. Each transcript was then manually processed according to the hierarchical content analysis procedure outlined in Table 2 (Krippendorff, 2004; Yin, 2003). Entries from the design diary underwent the same procedure. Table 1 sets out the content analysis codes. For transcribed sentences where no pre-defined code fitted, but the content seemed relevant, new emergent codes were defined. The encoding was therefore made from a developed theoretical position. It involved identifying connections between the data and the pool of available codes, relying (as is usual) on the researcher's personal familiarity with the subject matter.

Results – Influence of Clients

Work on the design and development of a new product is usually motivated or commissioned by a client or company seeking to make improvements to an existing product, or to move into a new product sector. The influence of clients defines the overall context within which materials and manufacturing selections are made, constituting a pragmatic 'starting point' for design decision-making, which is why it is the first to be presented. The guitar project was carried out in an academic context without a client, so the results presented in this section are derived only from the interviews.

Product Cost

Interviewees reported keeping within a target product price-point to be a crucial matter in materials and manufacturing selection. However, they stressed that low manufacturing costs should be as a consequence of an elegant design proposal, rather than a dominant driver itself. Designers stated that in general they specify the use of the least expensive materials that exhibit most of the properties they seek. It was reported that for some redesign projects, the target price-point could be so tight that simply opting for a slightly higher grade of material incurs an unacceptable cost.

Table 2. Content analysis procedure

Stage	Description
1. Coding	Transcribed sentences were scanned for keywords associated with the content analysis codes, and then coded accordingly.
2. Collating	Coded sentences were collated and assembled into code-specific tables. Asterisks were used to denote sentences receiving more than one code.
3. Reducing	Each sentence contained within the code-specific tables was reduced in content to a short paraphrase. Especially pertinent sentences were highlighted for possible use as verbatim examples. Internal consistency of data was checked at this stage.
4. Comparing	Cross-comparison was made of stage 3 tabulated data between all interviews, involving searches for occurrences, similarities, differences and patterns.

Design Brief Emphasis

Often a design brief will contain an emphasis to opt for one material or manufacturing process rather than another. Clients commonly expect designers to challenge conventional choices of materials and manufacturing, where a clear product or business gain can be identified. Table 3 reports on how different emphases impact on the selection of materials and manufacturing processes. A wide variety of products and materials illustrates the points raised by interviewees.

Brand Conveyance

The use of signature forms, details, interactions, colour schemes and so forth typically upholds a company brand, such that a Flymo lawnmower has a distinguishable product language from a Hayter, and thus a different appeal. The interviews reaffirmed the importance of materials and manufacturing processes as a primary brand conveyor (Dell'Era & Verganti, 2007; Lefteri, 2005; Ljungberg & Edwards, 2003; Olins, 1995). This strategic use of materials has similarities to the differentiation of products in hierarchical and niche markets. It can purposefully differentiate one company's full product range from that of its competitors to such a degree that the materials and manufacturing becomes a primary communicator of the brand. Indeed, interviewees stated that one way to rejuvenate a limp brand is to launch new products with an overhaul in materials and manufacture. For each of the products in Figure 2, the selection of materials, finishes and forming processes is a strategic corporate tool for conveying a brand, and not just a matter of fitness for purpose or sensorial attractiveness.

Predecessor Products

It was found imperative to take into account historical evidence of materials and processes selection from predecessor products. Considerable investment in time and resources usually surrounds companies' current choices of product materials and manufacture; the 'current way', in effect, is a result of learning about and responding to the shortfalls and mistakes of predecessor products. These can help designers avoid the mistakes of the past, as well as indicate plausible choices of materials and manufacturing selections for present-day marketplaces.

Results – Influence of Manufacturers and Vendors

The research established the central concern of manufacturers and vendors to be efficiency in the realisation of product components through manufacturing processes and materials. Their influence was found to manifest as product manufacturability, scale of production and material supply.

Manufacturability

The issue of manufacturability spanned three sub-topics: achievement of form, tooling complexity, and process tolerances. Table 4 lists the manufacturability issues raised during the guitar project.

Achievement of Form

Industrial designers seek striking ideas for product form to help build personality and appeal into their design proposals. This was found to create a significant challenge for manufacturability though, requiring designers to possess sufficient expertise to identify manufacturing routes capable of realising those forms. One interviewee stressed the issue very succinctly, "the most important thing to understand [is] how you are going to manufacture the thing that you have designed." Interviewees pointed out that poorly developed proposals for product form would inevitably undergo unfavourable modification in later project phases, being necessarily 'forced' to fit the working constraints of manufacturing processes.

Figure 2. Material and manufacturing as a primary brand conveyor.
From top: Matchbox toy cars (painted zinc alloy), Legnomagia kitchen accessories (beech), Apple MacBook Pro (aluminium alloy), LEGO toys (pigmented ABS), Global knives (stainless steel), Guzzini tableware (duo-colour PMMA), Tupperware containers (pigmented/translucent HDPE), Sigg bottles (coloured aluminium alloy), Koziol gadgets (transparent PC), Dyson appliances (pigmented ABS). Image permissions and credits are listed in the acknowledgements.

Table 3. Impact of design brief emphasis on selection of materials and manufacturing processes. Image permissions and credits are listed in the acknowledgements.

Emphasis	Description	Example 1	Example 2
Hierarchical market	Changes in material, forming process and finish can be used to differentiate products within hierarchical markets by affecting actual and perceived value (e.g. high-end, entry-level). • Example 1: Yamaha Motif XS7 high-end synthesizer (light blue treated steel) • Example 2: Yamaha EZ200 entry-level keyboard (grey pigmented injection moulded plastic)		
Niche market	Changes in material, forming process and finish can be used to differentiate the character of a product to appeal to different user profiles (e.g. fashion, business, youth, sports) or cultural acceptances. • Example 1: LG KF900 Prada mobile phone for fashionable appeal (high gloss plastic) • Example 2: Nokia 5500 mobile phone for sports appeal (matte plastic with rubber)		
Improved performance	Desired improvements in product performance can be paired to materials, forming and finishing processes (e.g. to reduce weight, improve strength, eliminate corrosion, widen temperature resistance, increase longevity). • Example 1: Rado Sintra scratch resistant watch (ceramic) • Example 2: Campagnolo Chorus Ultra Torque CT11s lightweight and stiff bicycle crankshaft (carbon fibre)		
Materials-inspired innovation	Materials-inspired innovation (Fischmeister, 1989) refers to a purposeful shift away from conventional materials and manufacture, and can be desirable in cases where traditional materials are diminishing, have negative connotations, or where material changes can bring product and commercial advantages. • Example 1: Green Toys range of plastic toys (recycled polyethylene from milk containers replaces virgin plastics and metals) • Example 2: Cool Acoustics FFS2002 acoustic guitar (polymers replace tonewoods)		
Simplification	Product simplification can be achieved through the design and manufacturing practices of (i) integration (combining two or more separate components into a single new component), or (ii) modularity (use of common components across product ranges). • Example 1: Biomega MN01 bicycle (superplastic aluminium integrated frame) • Example 2: Design Ceramic Tiles Arpuro S-Chair (decorative cast concrete mono-structure)		
Bespoke offerings	Product personalisation is becoming increasingly feasible and can be achieved through one-off and mass manufacture production. • Example 1: NIKE iD shoes mass customised from user-picked modular parts (mixed materials) • Example 2: FOC - Freedom of Creation Macedonia Tray using one-off rapid manufacturing technology (selective laser sintered quartz sand)		

Tooling Complexity

Industrial designers were found to be concerned with tooling only to a very limited degree. Although tooling *design* did not fall within their general responsibility, the interviewed designers were aware that adventurous product forms usually have a complexity implication for tooling (e.g. side action cores for injection moulding) and therefore an increased cost implication that must be justified.

Table 4. Manufacturability (M), material utility (U) and material supra-functionality (SF) arising during the guitar project

Identifier	Diary Entry Text	Areas of Design Brief	Diary Entry Numbers
M1	The difficulty of reproducing intricate details in a one-piece back using hand lay-up glass reinforced plastic (GRP).	1, 2, 5	46, 53, 57
M2	The difficulty of creating uniform rough surface texture in a hand lay-up GRP mould, and of releasing the associated shell from the mould.	1, 2, 5	236
M3	The need to prepare a GRP shell prior to painting.	1, 2, 5	307
M4	The use of vacuum-forming to create changes in thickness of wall sections.	1, 2, 5	85
M5	The ease of, and opportunities for, fabricating Forex-EPC (expanded polycarbonate).	1, 2	80, 105, 152, 153, 210
M6	For prototype fabrication and prospective mass-manufacture, comparison between the softening temperature and melting temperature of polycarbonate and Forex-EPC.	1	159
M7	Concerns for how different components of the guitar connect.	1, 2, 3, 5	6, 39, 47, 50, 51, 55, 58, 64, 91, 137, 142, 170, 296
U1	A desire that the neck material be smooth to aid playability.	1, 5	61
U2	Concern for the weight of the GRP shell.	1	305
U3	Concern for the density of polycarbonate and Forex-EPC.	1, 5	159
U4	A desire that materials exhibit musical resonance.	1	18, 63, 80, 89, 94, 198, 207, 223, 236, 260, 270, 294
U5	A requirement that materials are stiff to prevent flexing and to distribute sound waves.	1	12, 17, 55, 73, 94, 159, 192, 194, 226, 230, 284, 291, 305
U6	A requirement that assembled components can withstand forces due to tensioned guitar strings (particularly with respect to adhesive choices).	1, 4	107, 114, 128, 139, 141, 149, 151, 175, 260, 289
U7	A requirement that material used for the guitar binding and edging is flexible.	1, 5	196, 221, 234, 246
U8	A requirement that some materials dampen acoustic vibrations.	1	19, 38, 52
U9	A requirement that some materials resist scratches and dents.	1, 5	61, 83, 132
U10	A requirement that the colour of materials remains stable after sustained exposure to ultra violet light.	5	143
SF1	A desire for interesting qualities in the soundboard material.	5	4, 22, 225
SF2	"…I want the final product to have a dark grey, sophisticated look- but did not know exactly what the combination of colour and sheen was like [for the different versions of Forex-EPC]. [The black version] suits my requirements exactly- it has a really appealing overall visual quality. The black version really is special, and since I cannot paint the opal for fear of acoustic side-effects, I really need to get hold of some."	5	225
SF3	Opportunities for soundboard decoration, including a rosette and high quality printed graphics.	5	8, 80, 249, 252, 265, 270
SF4	Implications for perceived quality based on the assembly methods used in the instrument's construction.	2, 5	62, 98, 219
SF5	"The riveting (or screwing) idea came into my head a few days ago. Potentially interesting aesthetics- will consult [Rob] about technicalities."	2, 5	98
SF6	Use of a high gloss finish to highlight inherent properties of clear polycarbonate.	5	202, 224
SF7	Investigation of colour schemes of components.	5	215, 217, 222, 223, 254, 260, 261, 268, 306, 310
SF8	Neatness and interest in the soundboard edge finishing detail.	2, 5	221, 232
SF9	Neatness and interest in adhesive joints.	5	224
SF10	Neatness and interest in GRP shell surface finishes.	5	301, 308
SF11	A desire that materials have surface texture to help disguise scratches and dents.	5	132, 236
SF12	Possibilities for the incorporation of Rob Armstrong's logo into formed and machined components for visual and tactual effect.	5	224, 241, 247
SF13	Inherent surface finishes and contrasts between surface textures on a single component.	5	78, 309

Process Tolerance

Tolerances were revealed to be a driver in industrial designers' selection of forming processes, being linked essentially to component quality and consistency. The use of processes with very tight tolerances was acknowledged to increase costs, but this could be justified where improvements in product quality are sought, especially regarding assembly and the impression of integrity and engineering prowess conveyed by a product.

Scale of Production

This factor in design decision-making was described as a requirement for industrial designers to consider economies of scale and the 'break even' points of plausible forming processes with regard to anticipated volumes of production of a product (i.e. one-offs, small batches, mass manufacture). As stated by one interviewee, "you really can't start to think about form until you know the processes you are going to be using, and you can't start to think about that until you know how many you are going to be making." An additional finding was 'volume continuity', a term referring to the necessity to check that the manufacture of a multi-component product does not mix operations of a vastly different scale and cost. For example, an injection-moulded part (high volume automated process, low part cost) would not usually be combined with a metal spun part (batch manufacture manual or semi-mechanised process, high part cost). Such mismatches place strain on supply chains, and are usually not commercially viable.

Material Supply

Vendors are companies that promote, distribute and supply materials. The interviewees stated that maintaining a close relationship with vendors overcomes the problem of materials information becoming out of date. Importantly, vendors are a source of new material developments and material samples. For the guitar project, supplies of data sheets, samples, materials and adhesives for evaluation and prototyping were sought from vendors including Alcan-Airex, Ciba-Geigy, ICI, GE Plastics and 3M. Locally held stocks of materials were also used.

Results – Influence of Users

The interviewees reiterated that industrial design is a user-centred activity and that the subjects of materials and manufacturing should be treated from users' perspectives. As one interviewee stated, "materials are used to communicate to the consumer, it's part of the presentation, whatever the product may be." In response, industrial designers were found to select materials and manufacturing processes that deliver combinations of utility and supra-functionality. Table 4 lists product utility and supra-functionality issues raised during the guitar project.

Product Utility

Interviewees' examples of the contribution of materials and manufacturing choices to product utility touched on the following topics.

- Comfort (e.g. supportive and adjustable bicycle saddle – polyurethane foam?)
- Health (e.g. wipe-clean and corrosion-resistant cookware – stainless steel?)
- Information (e.g. night-viewable watch face – photo luminescent coating?)
- Safety (e.g. electrically insulated plugs – urea formaldehyde?)
- Usability (e.g. improved kettle grip – thermoplastic elastomer?)
- Usefulness (e.g. rigid monocoque chair – plywood?)
- Performance (e.g. lightweight tennis racket – carbon fibre reinforced plastic?)

Product Supra-Functionality

The visual and tactile properties of materials dominanted the industrial designers' construction of product supra-functionality. The interviewees emphasised that users do not interact with underlying 'raw' materials, but with highly finished materials (e.g. pigmented, spray painted, vacuum metalised, anodised). In fiercely competitive markets, such as handheld electronic consumer goods, interviewees described surface finishes as prominent in the marketing and sale of products, sometimes eclipsing utility or underlying concepts. One interviewee made this point especially clear: "I was trained with this sort of puritanical modernist type of thing that an industrial designer should only design and make models in grey, but when you really get out into the real market, it's so much finishes and colours and materials and feels that sell." We may deduce from the findings that designers' believe users are not so much concerned about how a product is made, or from which materials, but with the overall effect and impression that processed materials give. Material trends (projections for future uptake) and material fashions (here-and-now usage) were found to be an influence on product supra-functionality. However, these were noted to be less important considerations for products not residing on one's person.

The diary accompanying the guitar project provided three examples of the multilateral consideration of material-based utility and supra-functionality.

- Scratches, dents and cracks were identified as possibly weakening the mechanical integrity of the guitar (utility) and also negatively affecting appearance and hence perceived quality (supra-functionality).
- Ultra violet light, as a component of daylight, could over time seriously damage the mechanical integrity and longevity of the polymer (utility) and bleach vivid colours (supra-functionality).
- Ultrasonic joining of the guitar soundboard resulted in a very poor join, both structurally (utility) and in relation to appearance and touch (supra-functionality).

Figure 3 further illustrates the interconnectivity of material-based utility and supra-functionality, by mapping the considerations for the guitar project listed in Table 4 onto their associated regions of a prototype Cool Acoustics guitar.

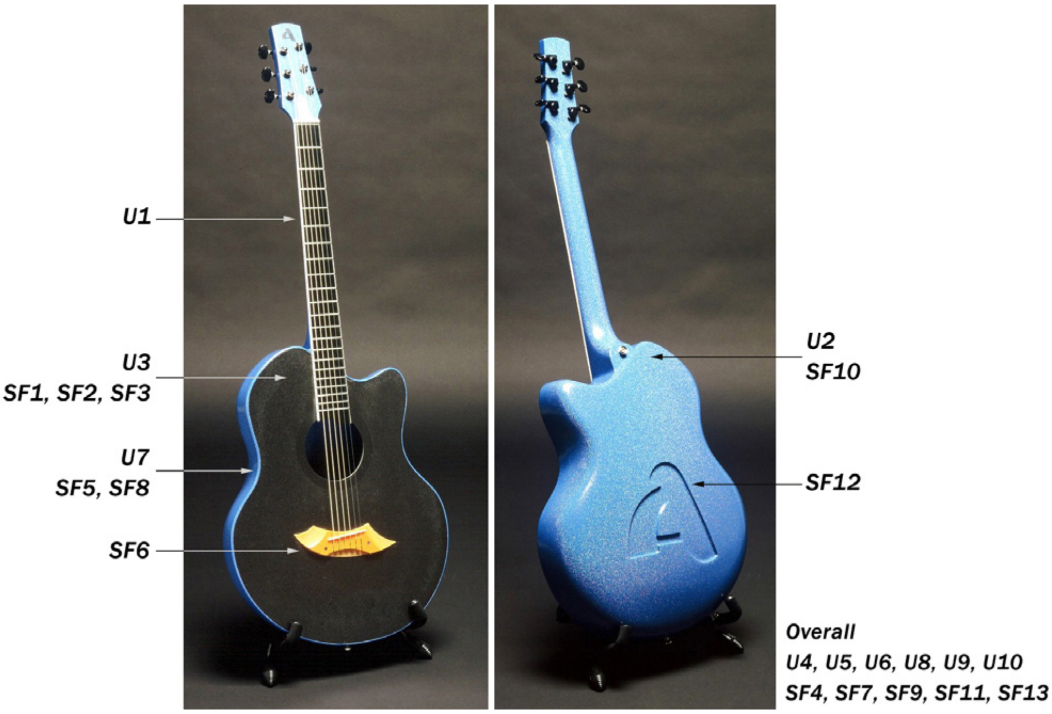

Figure 3. Product utility (U) and supra-functionality (SF) attributable to materials and manufacturing processes for the polymer acoustic guitar. The U and SF codes are listed in Table 4.

Results – Influence of Designers

The personal circumstances of a designer and their effect on materials and manufacturing selection should not be overlooked. A designer must take into account limitations on selection imposed by their employment context, and must also acknowledge that their personal expertise is a limiting factor on materials and manufacturing decisions.

Employment Context

An industrial designer's place of work and employment context has important influences on materials and manufacturing selection.

The variety of materials specified by designers working in-house within manufacturing companies (i.e. where the 'client' is the company's management, marketing or new business development department) was found to be limited to those for which supplies were held by the company, or those that had been used in the company's predecessor products. Thus, in-house designers work with a shortlist of 'proven' materials and available processes. As one interviewee put it, "80% must be ABS because most of our products are made of it." The opportunity to specify alternative materials was found to be limited unless exceptional circumstances applied, such as a company directive to adopt state-of-the-art manufacturing technologies, or a forecasted sales turnover that was sufficient to justify and absorb a shift to more expensive materials.

In contrast, design consultancies are involved in a diverse range of design briefs, these being found to require wider experience in materials and manufacturing than is needed for in-house designers. Such variety makes consultancy especially engaging, but brings pressures of designing for less familiar materials.

Expertise

Designers' personal expertise in materials and manufacturing, represented by intellectual attributes including knowledge, values and skills, is an important influence. Domain expertise for industrial design was found to span four selection activities: materials, forming processes, supplementary finishes, and joining methods. The nature of industrial designers' intellectual attributes for materials and manufacturing is the focus of the epistemological analysis of the research data.

Results – Design Engineer and Designer-Maker Practices

The results of the design engineer and designer-maker interviews gave insights into how the two professions differ in their treatment of materials and manufacturing selection.

Specialty

Although product utility is important to designer-makers, who create artefacts with clear practical uses, they are especially concerned with eliciting emotional responses from the people who own and use their artefacts. Thus designer-makers are experienced in the unity of human factors with sensorial-based materials and manufacturing choices, where artefacts are designed to possess considerable supra-functional qualities. Much effort is directed towards the achievement of diverse and distinctive material finishes and decorations. Design engineers tend to look at choices of materials and manufacturing once schemes and calculations for achieving desired component utility and form (i.e. static and dynamic mechanical specifications) have been proposed, and use quantified material properties in their decision-making.

Materials Variety

Design engineers possess expertise across several material families, notably metals and plastics. In contrast, designer-makers are typically experienced in working within a single material family, woods, ceramics, glasses and metals being dominant. Specialisation in plastics is rare. The material variety for designer-makers is therefore limited to availability within a material family. The ceramicist, for example, has two basic material choices: white earthenware (a relatively cheap and unrefined clay) or bone china (an expensive, high quality clay that has translucency similar to porcelain). Furniture designers specialising in wood usually choose between softwoods, hardwoods and wood-derived composites.

Product Variability

One of the central principles of engineered components is that they may be reproduced with near zero variability and therefore possess predictable performance when assembled into a product. Design engineers therefore equate quality with product consistency. For designer-makers, product inconsistency brought about by variability in material sensorial properties or by manual making processes is viewed positively. Such variability is valued in craft products, being associated with individuality and preciousness. Designer-makers' skilled exploitation of variability in material properties makes their artefacts highly prized. People embrace a 'handmade aesthetic' within designer-makers' work.

Involvement in Manufacture

Design engineers will rarely manufacture their creations themselves, however they may be personally involved in prototyping for test purposes. Usually production will be commissioned or outsourced to a manufacturer. Thus, design engineers must make explicit the final specifications of a product proposal (e.g. through computer models, part drawings) so that manufacturers can implement its production. In contrast, and by definition, designer-makers personally undertake the physical realisation of their designs. Because there need not be any other person involved in the designer-makers' practices, it is reasonable for plans for materialisation to exist only in the maker's mind; there may be no requirement for an explicit plan to be made or 'handed over'.

Scale of Production

Product proposals prepared by design engineers are commonly destined for mass production by industrial manufacturing processes. However, design engineers are occasionally involved in the creation of one-off products for a specific commission. In contrast, because designer-makers also manufacture their creations, the availability of time and labour severely limits their abilities to produce on a large scale. Occasionally, designer-makers based in relatively large studios and with an accompanying workforce can achieve low volume batch manufacture through the aid of modest industrialisation.

Discussion

The implications of the results for answering RQ1-3 are now discussed.

RQ1 – Identification of Stakeholder Influences

Stakeholder influences on industrial designers' selection of materials and manufacturing processes have been identified through the study. The combined influences are collated as a graphical representation (Figure 4), intended as a quick visual guide. The guitar wireframe is representative of any industrially designed product, in this case referencing the guitar project. Users are placed directly alongside the product representation, to emphasise that they are the final judge of a product, irrespective of the intentions of designers, clients and manufacturers/vendors. The purpose of Figure 4 is not to turn decision-making into a formulaic activity, but rather to enrich it by making explicit the wide range of variables that can and do inspire creativity in materials and manufacturing selection.

It can be said that each stakeholder in Figure 4 brings a collection of influences that reduces, sets direction, or otherwise 'drives' materials and processes selection activities. The influences may be characterised as follows: strategic/commercial (clients), feasible/obtainable (manufacturers and vendors), perceptual/experiential (users) and circumstantial/personal (designers themselves). It is important to note that a scoping study such as described in this paper cannot claim to comprehensively document all stakeholder influences. For example, an additional factor not mentioned is the practical impact of *sustainability issues* on materials and manufacturing selection, which was outside the remit of the research. Another evident exclusion is influence arising from regulatory, standards or governmental bodies and concerning health, safety and environmental issues. Nevertheless, the prevalence of repeat responses gathered across the interviews is presented as reasonable vindication of a good level of coverage. It is important that further studies are made to expand on the scope of this first round of insights, including the development of Figure 4 into a general model encompassing relative importance weightings.

RQ2 – Consideration and Management of Stakeholder Influences

The study revealed that most stakeholders, with the exception of clients, rarely make proactive approaches to designers or in other ways *exert* influence on materials and manufacturing selections. It was found that in most circumstances designers are responsible for identifying, initiating and synthesizing the various stakeholder influences.

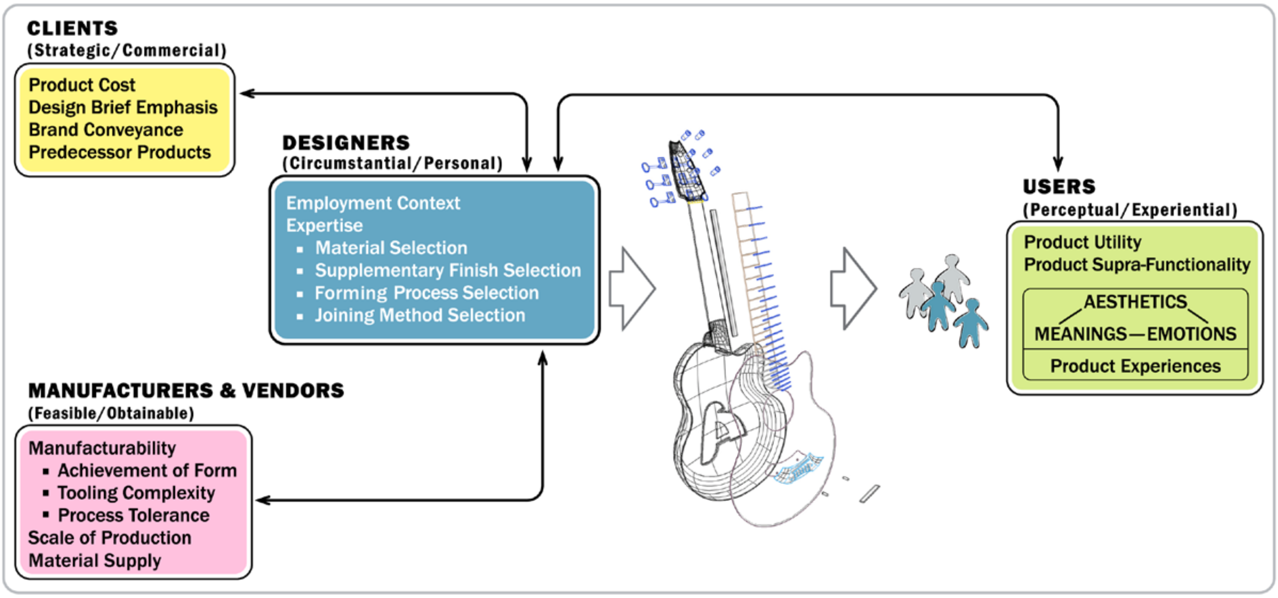

Figure 4. Collated stakeholder influences on industrial design materials and manufacturing selection.

In Figure 4, although designers are placed at the centre, their selection activities are far from self-centred. The industrial designers interviewed were vehement that creativity in materials and manufacturing selection depends on attending to stakeholder influences, and is not based on unconstrained freethinking. Some especially pertinent comments were as follows: "limiting materials and manufacturing knowledge also limits designers' ability to spot opportunities", "skill comes in being creative within the boundaries of the production processes and the costs that you've got to meet", "if you don't know [the practical constraints], or you haven't really got them lined up in front of you, you don't know what the hurdles are that you're trying to jump." This finding resonates with the educationalist Pring's (1995) contention that creativity cannot be exercised within a context of ignorance. Figure 4 identifies the 'hurdles' and makes explicit the arena in which designers must exercise their creativity, ingenuity and coordination. Hence the links between designers and other stakeholders in Figure 4 are shown with two-way arrows to indicate negotiation. The only exception to due consideration of stakeholder influences was identified as design competitions, which encourage thinking beyond the boundaries of available manufacturing technology. These were found to be a source of imaginative release for designers, away from commercial realities.

The study uncovered some valuable insights into the dynamics of each stakeholder's influences, and designers' management of those influences.

Clients

As the initiators and sponsors of projects, the influences of clients (or in the case of in-house designers, other sections of their employing company) on materials and manufacturing can be very direct. For example, the interviewees revealed that some clients have ideas about changing an existing product from *process a* to *process b*, and ask designers to assess the feasibility and opportunities for this. Within the larger manufacturing companies interviewed, it was common for materials and manufacturing information to flow from specialist R&D sections to in-house designers, specifically to stimulate new design ideas. It is clients, not designers, who set parameters for product cost and materials emphasis within design briefs, whereas designers were found to be responsible for conveying a brand through materials and processes selection, and for researching predecessor products. The guitar project was carried out without a client and thus revealed no client-designer relationships.

Manufacturers and Vendors

The consultant designers interviewed stated that they approach, meet and liaise with manufacturers to find out about facilities, resources and any special design implications arising from preferred tooling suppliers or tooling restrictions. Thus consultant designers often establish new conduits between clients and manufacturers. For the guitar project, manufacturability, scale of production and material supply issues were also designer-initiated, with the author approaching manufacturers and material vendors, never the other way around. The consultant designers stated that in some circumstances, clients have pre-existing relationships with manufacturers and vendors, and request designers to maintain these connections. It was found that vendors occasionally proactively supply samples of new materials to designers in anticipation that those materials may be specified in new products.

Designers working in-house at manufacturing companies are essentially *instructed* by their managers to use a certain material and for their design proposals to be tailored specifically to in-house manufacturing facilities. This situation represents the most extreme influence on industrial designers' selection activities. However, because of their employment situation, in-house designers are well positioned to 'police' their design proposals to ensure that design intent is fully realised in the resulting production artefact, which is not always possible with consultancy work. Furthermore, large multinational companies work closely with material vendors because of the quantity of materials that they order. On a corporate level this relationship is two-way; interviewees stated that new materials and finishes are sometimes developed specifically for a company's new product development programme. However, the final choice of material vendor and precise material grade to be used in a new product is usually made by the company's purchasing department, with little or no involvement of industrial designers.

Users

The interviews uncovered no substantial evidence that users have *direct* involvement in designers' selection of materials and manufacturing processes. This is not surprising, since user-material relationships are complex and tools and design methodologies to assist user-centred material selection activities are only just emerging (Karana et al., 2009; van Kesteren, Stappers, & de Bruijn, 2007). The interviewees made brief mention of user requirements arriving via the marketing and sales departments of clients or employers. Throughout the guitar project there was a similar lack of user-material consultation, specifically because the project involved a technical task to develop and prove new technology rather than to develop a market-oriented product. User-centred materials and processes selection was therefore carried out *by proxy*; consulting books, the Internet and other such sources, essentially making executive decisions in the absence of direct user involvement. The findings underlined the need to develop user-centred material selection tools and methodologies.

Designers

The interviews and guitar project both established that colleagues and consultants, as part of an extended design team, pool their expertise in relation to user requirements, materials, manufacturing, assembly, and prototyping/testing. Thus designers have ready access to diverse and relevant information, which may be requested of, or volunteered by, a colleague or consultant.

RQ3 – Crossovers with Design Engineers and Designer-Makers

Industrial designers' involvement with materials and manufacturing has closest ties with the engineering design profession, however important crossovers exist with designer-makers. Table 5 provides a summary of the findings of the study. The columns marked 'ID?' indicate whether the various responsibilities and perspectives are found in industrial design practice. The following observations can be made and are organised according to the aspects raised previously in the paper.

- **Specialty**. A defining aspect of the industrial designer's specialty is the consideration of materials as a 'user interface', with associated focus on sensorial material properties. This was usefully summarised by two of the interviewed industrial designers: "materials and processes are where you can add some spirit to your design" and "form, visual language, the emotion of the product is always going to be there rather than just the manufacturability, the cost-effectiveness, the production ability."
- **Materials variety**. Although plastics are dominant in industrial design, projects often require familiarity with other materials, especially metals and elastomers.
- **Product variability**. Product designs proposed by industrial designers are realised as industrially manufactured components, usually with the high level of consistency associated with engineering. However, contemporary manufacturing solutions offer ways of achieving purposeful variability in products, applying the designer-maker's preference for unique features, but on an industrial scale. Rapid manufacturing technologies and mass customisation are two such ways, raised in Table 3. Another is the incorporation of random elements within CNC (computer numerically controlled) machine code, to apply unique patterns and surface finishes to products (http://www.vectric.com/). Yet another is the use of forming processes that results in random final forms, for example the *Sponge* polyurethane armchair by Peter Traag for Edra (http://www.edra.com/product.php?id=42&name=Sponge), which has irregular upholstery folds.
- **Involvement in manufacture**. Industrial designers, as with design engineers, rarely manufacture their creations themselves and similarly need to make the specifications of their proposals explicit. However, they will often be directly involved in prototyping and the creation of mock-ups to assist design development.
- **Scale of production**. As with design engineers, industrial designers are involved in projects ranging from one-offs to mass production.

Table 5. Comparison of aspects of design engineers', designer-makers' and industrial designers' attention to materials and manufacturing

Aspect	Design Engineer	ID?	Designer-Maker	ID?
Specialty	Utility	×	User interface (utility and supra-functionality)	✓
Materials variety	Expertise across material families	✓	Expertise in one material family	×
Product variability	Variability is undesirable	✓	Variability is desirable and valued	✓ (rarely)
Involvement in manufacture	Plans but does not undertake manufacture	✓	Personally undertakes manufacture	✓ (mock-ups)
Scale of production	One-off to mass production	✓	One-off to batch production	×

Conclusions

The study has sought to strengthen the methodological base underpinning materials and manufacturing selection in industrial design. It has elicited important stakeholder considerations from one case study and sought a sense of the general validity of the results through interviews with industrial designers.

Attention to materials and manufacturing was found to be a fundamental concern in industrial design, not a peripheral activity. Criticism that industrial design is a styling and semantics profession, disconnected from production realities, was not corroborated. Industrial designers were found to reach decisions on product materials and manufacturing by mediating influences attributable to clients, manufacturers/vendors, users, members of their design team, and their personal expertise. The primary achievement of the study has been to identify for the first time these various stakeholder influences and collate them into a single resource. The study has revealed insights into how designers manage the stakeholder influences and coordinate their integration into selection activities. Under most circumstances, the flow of activity was found to be initially from designer-to-stakeholder, rather than stakeholder-to-designer.

The study has successfully exposed the ways in which industrial designers contribute to the task of product materials and manufacturing selection and revealed that this manner is complementary, but in many ways similar to engineering colleagues. This was achieved by examining professional crossovers between industrial designers, design engineers and designer-makers. Because industrial designers' activities are focused on the conceptual phases of product design, their expertise in downstream detailing for manufacture is limited compared with that of engineer colleagues. However, their defining attribute is to regard materials as a product user interface, directly affecting users' experiences of product utility and supra-functionality. Such a perspective has strong crossovers with designer-maker practices. Thus user-centred approaches to materials and manufacturing selection are a key characteristic of industrial design.

Academics can use the new insights gained through the study to devise improved materials and manufacturing information resources and training targeted specifically at industrial design students. Design managers can also use the findings as a way of levering maximum contributions from their industrial design staff.

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