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LACK OF INTEGRATION BETWEEN ENGINEERING INDUSTRIAL DESIGN PROCESSES: AN ANALYSIS BASED ON THE HISTORICAL EVOLUTION OF PROFESSIONS AND TOOLS

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ABSTRACT
Numerous researches provide evidence that Industrial design is key to trigger, foster and sustain innovation and can lead to a measurable performance growth of the business. Nevertheless, their integration with the engineering design process has been difficult since the birth of the profession. The lack of dedicated design tools responding to their specific needs is one of the most important reasons for this stagnation. In this paper we propose an historical and technical approach to trace the evolution of digital design tools. It appears they can be classified inside two archetypal categories. The first one has been designed to address the needs of the engineers such as the reusability of design for manufacturing purposes. The second one was made for graphical artist, for artistic composition or with the capacity to animate and render three-dimensional models. The industrial designer profession use tools with qualities from both categories – neither of which have been designed for her specific needs. We detail the technical reasons for this evolution and we argue it might be possible to solve this issue with a holistic consideration of both approaches.

Keywords: computer aided design, CAD, industrial design, engineering design, compatibility

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"If the only tool you have is a hammer, you tend to see every problem as a nail."
Abraham Maslow

1 INTRODUCTION

Industrial firms are struggling in a deadly competition. They make most of their profits on new products (Le Masson, Weil, & Hatchuel, 2006) that imply a renewed and continuous capacity for innovation. As a great number of studies tend to show that industrial design is key to trigger, foster and sustain innovation (Borja De Mozota, 2002; Verganti, 2008) which leads in most cases to a measurable performance of the business organizations (Berkowitz, 1987) the firms try to integrate them.

But ID (Industrial Designers) always have been very difficult to integrate into the engineering design processes since the birth of the profession (Loewy, 1963) for various and numerous reasons. Collaboration with the other design professions like engineers and product managers appear to be impeded by strong differences in design languages. (Von Stamm, 2008). These differences can also be characterized by a focus divergence on what are the means and ends to achieve a good design and the type of innovation they have the capacity to reach (Rampino, 2011).

Another important issue for their integration is the lack of dedicated digital tools supporting their activities. While they are still reluctant to abandon the traditional media issued from their artistic education (such as sketch or mockup) their digital counter parts, 3D (Three-Dimensional) sketching; (Bae, Balakrishnan, & Singh, 2008) or digital clay (Barone, 2004) share the same flaws. The models they generate are not compatible with most of the engineering design software. This transition creates a design-gap (Dorta, Perez, & Lesage, 2008) were the concepts created by industrial designers are modified beyond their control. When they try to by-pass this issue by using tools created for engineering design needs and purposes, they confront the even more delicate issue of losing their creative productivity since those tools have not been designed for creativity or industrial design concerns such as the aesthetics. **This is a conundrum that industrial design professionals often face**: in most cases, *either they need to borrow and work with tools not specifically tailored for them, or, to use tools adapted to their needs whose outputs cannot be integrated into the downstream design process since engineering design tools do not preserve the flexibility and properties of the digital media they produce.*

These are huge obstacles considering the necessity to better articulate these two professions. Aside from various organizational perspectives to solve this issue, we suggest that a particularly important enabler for better integration of industrial and engineering design professions and practices would be through the integration of their toolkits for design. To this end, the current paper defends that we first need to better understand the evolution of digital design tools and how industrial designers came to the conundrum they struggle with today.

The current paper suggests a review of the historical evolution of design tools (Bozdoc, 1999, 2003; Farin et al., 2002), mainly for engineering design and graphical art. In both cases, the need created by the evolution of the profession is sooner or later responded to with a technical breakthrough (e.g. Bézier curves or polygonal surfaces) The review shows that a) generally, **the evolution of design tools was deeply linked to the evolution of the corresponding design professions**, b) **industrial designers who had difficulty in abandoning traditional physical tools such as mockups were naturally pushed to adopt existing tools** (built for the engineer or graphical artist) when they did so.

Section 2 starts with the review of the evolution of engineering design tools. Section 3 reviews the evolution of graphic art tools (we include in this broad categories tools from 2D graphic creation to 3D animation tools and technologies). Section 4, discusses the origins and practice of industrial design and reveals specificity of tools needed for the holistic approach of industrial designers. Obstacles are discussed with respect to the currently used technologies in engineering design and graphical art tools. We conclude by discussion how a new class of hybrid tools with very specific properties could address these issues of integration.

2 EVOLUTION OF ENGINEERING PRACTICES AND REPERCUSSIONS FOR ENGINEERING DESIGN TOOLS

In the following, we will start with explanations about how the engineers were able to manufacture their own digital tools, with a perfect fit to their daily design tasks. The functionalities of engineers' design tools were directly influenced, if not imposed, by the industrial challenges they dealt with.

2.1 Pre-computer era: Reusability and speed already as fundamental needs for engineering design

The first recorded use of curves for manufacturing intend was in early Roman times for the purpose of shipbuilding. The designers used templates and full size drawings on the ground to produce ship's ribs, thus a ship's basic elements could be *stored* and did not have to be redesigned every time a new vessel needed to be built. Even back then, the reusability of designs was essential and the principal goal. This early form of "parametric design", the origins of which can be traced back to the *Elements* of Euclid as early as 300 BC, was later perfected by the Venetian naval industry. Venetians were able to produce series of ship from the same reference at previously unachieved speed and reliability (Lane, 1992).

Same issues and concerns were preserved through out design history. Early design theories such Redtenbacher (1848) had the ambition to teach craftsmen and engineers how to produce efficient and standardized machine designs. The method pre-supposed the machine architecture is known and the design effort is about the dimensioning of the different parts, based on a maximal reuse of knowledge. One of the most influential design companies in early 20th century, the Boulton Locomotive Works (Le Masson et al. 2010) were using also a parametric design approach facilitating reuse of previous design episodes. Once the parameters calculated and known the designers had to build instructions for the downstream manufacturing. Their prescription media was mainly blueprints that were drawn and then transmitted to the factory.

Fifty years latter this method of mass design was dominant in the industry and with the generalization of mass production at the beginning of the 20th century in the industry, mostly under the impulse of Ford in the newly born automotive sector, for the reusability of an increasingly complex knowledge, the choice of design tools became even more critical. The designers, draftsmen and engineers, were conceiving the blueprints and plans with pen and papers. This technique was extremely long, lacked reusability and was source of errors. Then it is not surprising that the promise to surpass all these flaws simultaneously with computer programs seems like a holy grail for these firms after almost 50 years of difficulties, from 1900 to 1950. It is very interesting to note that the impulse did not come from the designing side but rather the manufacturing one.

2.1.3 Design for manufacturing: the first impetus towards computer aided design

A major shift occurred in design practices by the apparition of CNC (Computer Numerical Control) machines that provoked dramatic changes in engineering design practice. The first industries that can afford such technologies, very expensive by then, were the automotive and aircraft industries, albeit their priorities were different (Scranton, 2010).

The automotive industry, dominated at this time by the *Big Three* (Ford, GM and Chrysler), was looking for a simpler way to produce CNC machine instructions for the milling of various shapes. The early models of CNC machine were fed with punched tape and their users had great difficulties determining the right trajectories of the milling tools. With the progressive apparition of programmable and faster units this issue became very stringent. The initial main use of computers was indeed not to model complicated surfaces and volumes but simply to *produce the information necessary to drive the tool*'s trajectories of milling machines.

A lot of tentative have been made to come up with tools to help the engineers to draw the trajectories instead of sampling and defining all the points through which the tool needed to pass. The most successful was from Pierre Bézier, a French engineer working for Renault, introduced a most ingenious technique method for defining curves. Instead of defining a curve through its points he used control points placed on the tangent lines, allowing both a better drawing experience and an easier control for adjustments (Bézier, 1972). In its most basic form, a Bézier curve is made up of two end points and directional control handles attached to each node. The control handles define the shape of the curve on either side of the common node. The breakthrough insight was to use *control polygon*. Instead of changing the curve (or surface) directly, one changes the control polygon, and the curve (or

surface) follows in a very intuitive way. This technique of drawing is still in use in most of the design software either in 2D or 3D environments. Based on this technique, Bézier designed the software UNISURF that was the precursor of most of the CAD (Computer-Aided Design)/CAM (Computer-Aided Manufacture) software still in use today (Bezier, 1986).
The aircraft industry had different requirements even if they ultimately also needed to manufacture parts using CNC machines. During the post WW2 context a technology boom occurred: because this domain was using specialized, cutting-edge technology for the development of high-speed and high-altitude aircrafts, they needed adapted tools. Their flexibility was then critical, for devices and components to be redesigned after failures in testing or use mandated serial adjustments in materials, processing and machining setups.
They had the constant need of revising and reusing blueprints that the paper made very cumbersome (Farin, Hoschek, & Kim, 2002). They also had the need to produce a *large variety* of representation of their assembly, sometimes in full scale, which is rather quite different with respect to automobile industry. This necessity to speed-up and make it more reliable the management of complex blueprints explains why aircraft builders, such as Lockheed Martin, developed their own CAD solutions. The project began in 1965 under the name "Project Design" and was implemented on IBM 360 computers (Weisberg, 2006).
The software was designed to integrate *parametric manipulation* of shapes were each objects such as *lines*, *points*, *circles* was parameterized and then applied functions such as *offset* and *dimensions* for the most basics. With this functionality design changes were easier to integrate. This software, with significant historical importance for CAD tools, was called CADAM (Computer-graphics Augmented Design And Manufacturing). It was very powerful and its properties soon promote its use used for other usages, such as the production of electric diagrams, with an unseen precision.

2.1.4 The apparition of new hardware generates new software capacities

In Lockheed Martin's CADAM, IBM's 2250 graphics display terminals were used as shown in Figure 1. On these terminals a light-pen as a pointing device which allowed a very intuitive and easy way to interact with computer diagrams (Weisberg, 2006). This interface technique is based on the work of (Sutherland, 1963) and makes easy the selection of displayed entities. The user could directly select and trace entities rather than requiring the computer to indirectly match a coordinate input from a tablet device to the drawing database.
Eventually, the use of light-pens has been abandoned in favor of a much cheaper and more precise way to interact with displayed graphics: the mouse (English, Engelbart, 1965). The engineer, who needed more precision for an acceptable cost adopted this new technology, while, ID was still clinging to sketching pen and physical prototypes, an opportunity to integrate both worlds has been lost.

Figure 1. IBM 2250 Display connected to an IBM 1130 Computer

2.1.5 From 2D to 3D

In 1974, the company Dassault Aviation was one of the first licensees of Lockheed's CADAM software that was used for 2D (Two-Dimensional) drafting work. But its limitations called in 1978 the company to develop a 3D in-house design tool to address some specific parts of the process such as the design and assembly of plane wings. It was necessary to have precision at the level of microns on parts that were sometimes bigger than dozens of meters and these very complex shapes and managing or assembling them with 2D blueprints was very difficult. The company developed its software starting on the core of CADAM and created a module announced in 1981 under the name CATIA (Computer-

Aided Three-dimensional Interactive Application) Version 1. Its principal capacities were 3D design, surface modeling and NC programming (Daloz, 2010).
Used both for modeling applications and the machining of surface geometry, CATIA made it possible to reduce cycle times, improve quality and optimize production efficiencies. At this time models where represented with wireframes due to the display technology of screen (vector tracing) and the visualization only seen as an extra, the core being to produce manufacturable data. This capacity to design entirely complex 3D objects eventually pushed the physical mockup out of the picture: in 1990 Boeing started designing its new 777 only on computer, going fully digital (Daloz, 2010).

3 DIGITAL TOOLS FOR GRAPHICAL ARTISTS

This category of tools have legacy in two academic fields of literature which merged latter on. According to (Umbaugh, S.E., 2005) the field of image processing grew from signal processing, while the computer science discipline was largely responsible for developments in computer vision.

3.1 The first digital images and 2D Software tradition

The first digital photograph was made of just 176 x 176 pixels and presented by a team directed by Russell A. Kirsch in 1957. They used the computer to extract data from an original photography and displayed the digital image on an oscilloscope screen. For the first time a computer was used for displaying a graphic content, it was the premise of all upcoming computer imaging.
The tradition of digital imaging gave birth to a lot of 2D illustrative software that are still widely used today for graphical illustration by ID. The most famous creative suite is the one from Adobe, with Photoshop and Illustrator. Photoshop was at first dedicated for digital images editing but it is now widely use for the creation of digital content with its drawing capacities. Illustrator was at first a font editor but its vector graphics editor capacities made it soon the reference for drawing with vectors. It heavily relies on Bézier curves for the drawing of shapes and curves. What was once a drawing technique for milling tools is now widely use for the generation of artistic graphics. They both have the possibility to be interfaced with graphic tablets with stylus.

3.2 Interactive graphics: a common ancestor with engineering tools, SketchPad

Displaying was one step; the other one was the capacity to interact with the computer more naturally than with the input of code and command lines. The work of Ivan Sutherland who in 1960 used a TX-2 computer produced at MIT's Lincoln Laboratory to create a project called SKETCHPAD, which is considered the first step of drawing interface. Even if its prototype worked with a light-pen at this time its principles have legacy in every WIMP (Windows Icons Menus Pointers). The term was coined by in 1980 by Wilberts (Nesheim, E. 2011) interfaces and still worldly used.

3.3 The strong influence of the entertainment industry for the 3D software

3.3.1 First wireframe representations for the entertainment

With these two bases we have to wait until the late 70’s to see the first commercial applications of this type of products. This could be easily explained by the fast price decrease of the computers and their increasing processors capacities, as Moore prophesized (Schaller 1997), this enables the apparition of the personal computer and the number of users and fields of applications sprouted in every direction. Magazines such as ANALOG (Atari Newsletter And Lots Of Games) published and shared line codes among various communities in the early 1980’s.
Computer graphics were used to create 3D wireframes in the domain of entertainment. This was a need pushed by the film and series making industries and the science fiction because these hi-tech special effects gave the movies a futuristic look, never seen before. A lot of TV series such as Galactica and Star Trek required the intensive use of CGI (Computer Generated Imagery) effects. The movie Star Wars Episode IV: A New Hope also participated to the need to create structure capable of developing such technologies. It caused George Lucas to found the to be famous Industry of Light and Magic in 1975. This company is responsible for the special effects of most of the Hollywood super-production primed for their special effects such as Back To The Future (1985-1990), Terminator: The Judgement Day (1991) and Jurassic Park (1993).

Figure 2. (a) Polygons drawn over a hand mock up for 3D registering of defining dots; (b) Digitalization of the hand with a 3D pointer which records all 3 coordinates.

3.3.2 Polygonal modeling: a technique with specific advantages

The wireframe was a first step needed for the representation of 3D objects but it only specified the contours and made images with distant looks to as we see things in reality, surfaces which absorbs, transmits or reflect light. Once the computers became powerful enough to generate dynamic 3D models in wireframes they quickly gained the capacity to process what is called surface models.
The polygons could be build and define with wireframes and are the most basic surfaces possible they therefore offered a very practical mean to define a 3D surface. A polygon is composed of triangles characterized by 3 dots in the space, 3 edges linking them and an orientated surface. They have several advantages:

– The polygons are very easily defined and the operators for modifying them rely on *simple metaphors* such as *displacement and scale*. When a user models an object he has to position the polygons but he does not have the imperative to manipulate dedicated design functions such as in the case of engineering digital design tools. The polygons are a very scalable material that means that with practically no cost a model can be refined simply by adding smaller polygons. Therefore an artist could best fit the capacities of the machine displaying them for a good rendering. At the beginning of the art polygons were also a very efficient way for scanning 3D real objects. The mockups were made of polygons (see figure 2 (a)) and the user had a way of registering one by one each coordinate of each dot and line composing them (see Figure 2 (b)).

– This modeling technique made easier the *possibilities of animation and deformation* of geometries. The deformation of polygons is easy to handle as it is only a displacement of the dots defining them. As the dots are moved into the space by commands, key frames are stored. The software calculates the deformation between the starting and ending point.

– The polygons are ideal for calculating the lighting of objects. The software can simply calculate the reflection angles given by each polygonal surface. The rendering, i.e the aspect of display, of each surface is calculated by the computer according to lighting conditions, the material and colors of the polygon, etc… The final rendering is the sum of all reflections of all the polygons composing the surface. With a direct control on the polygons the artists could *easily control their surfaces* and *their reflection* before the final optimized rendering because they had the access to what the surface would be made of. They are also use for the skinning operation when the artists need to position a texture on geometry. He starts by unfolding it and then he defines on the 2D surface decomposed in polygons exactly where the texture is positioned.

3.3.3 The subdivision technique, making smooth polygons in a click

Another step was taken when Ed Catmull introduced with John Clark the subdivision technique: they built an algorithm to uniform cubic B-spline curves and its tensor product counterpart (Catmull & Clark, 1978) from the work of the artist G Chaikin.
With this technique it is possible to manipulate polygonal meshes and then to transform them into smooth surfaces by a process of “chopping of corners” in a reversible fashion. This novelty was significant for Industrial Designers as it offered them the possibility to refine their geometric designs with polygons they could entirely edit to their will and *then* apply the smoothing options. The smoothing could be more or less iterated providing a satisfying processor and graphical use when preparing the model and then pushed to the max to obtain nice and smoothed surfaces for rendering. It is the dominant modeling technique in this category of software.

Figure 3. In 1972 Ed Catmull (founder of Pixar) and his colleagues created the world's first 3D rendered movie, an animated version of Ed's left hand.

4 IMPACT OF ENGINEERING AND GRAPHIC ART TOOLS ON INDUSTRIAL DESIGN PRACTICES

4.1 Industrial design: a design profession with a holistic approach

Along with engineers and 3D artists, another profession in need of digital design tools is the ID. (Forty, 1992) explains the appearance of ID in the beginning of the 19th century; in an industrial revolution era in Great Britain, the design process started to drastically change. Instead of craftsmen working alone and designing unique objects, an industrial organization appeared with managers and a working class. For manufacturing serial production, the newly born companies needed to design their products, first by copying older products (e.g. the Portland Vase of Wedgwood) and following the tendencies (e.g. strong demand of the consumers for antic art furniture and dishes). The firms started to contract with professionals able to design and represent products which will sell (which means with aesthetical and stylish properties) and could be manufactured in pre-industrial process with a quality standard. Linked by these two imperatives**, being neither artists nor technician but sharing competencies from both these worlds**, industrial design was born.

One of the most emblematic of them was Raymond Loewy. Iconic designers like him could determine the success or failure of products appeared. He was a French engineer with an original background: he first produced illustrations for Vogue and Harper's Bazaar in the fashion industry. He then opened his own office in 1929 and made its first renowned product, a restyling of a Gestetner’s duplicating machine. His idea was to fit the technical parts of the product under a stylish hull to ease the dirt and noise it produced. His most famous productions count in the Greyhound bus, the Studebaker Avanti and the Lucky Strike logo (Loewy, 1963). With Loewy the relationship between creative/artistic designers and industry became so strong they begun to be called ID. During his carrier we can find all the different specialties this profession addresses: graphics, transportation, product, packaging… Each time, they are deeply linked to the industry and the manufacturing of products. But as we will see industrial designers suffers from a particular curse since Loewy: **they need to control or master the final appearance and usage of a product by only giving an approximate definition at the beginning of the design process**. Moreover, they mostly rely on a limited and traditional tool bag such as mockups and sketches to work with.

Figure 4. On the left Volt concept Car, great success at January 2007 North American International Auto Show. On the right Volt serial car 2011. During the time some notably changes happened in the “package” (global dimensions of the car) which had hard impact over its final style and market success.

Both engineering design and graphical art professions were able to reuse the knowledge developed by academicians in the field of mathematics and computer science to create their own software. But because they do not share a lot in common (they manipulate different models, do not have the same capacities for manufacturing, editing, animating and rendering) they are usually not compatible (and it can be even more difficult with the massive use of 2D tools at the beginning of the process). Transforming objects from one world to another is possible but a lot of data is lost in the process (Kim, Pratt, Iyer, & Sriram, 2006). And we can here see the dilemma that the industrial designers are facing. The industrial companies who hire them ask them to produce creative concepts. To be able to express freely their ideas they tend to use tools from the artistic world but these are poorly compatible with the industrial CAD tools (Arrighi, Le Masson, & Weil, 2012). On the other hand the engineering CAD tools are very well integrated, as the reference media for design. But being designed for the engineers they tend to dissect and decompose designs which contrary to the holistic approach of an industrial designer. As such, engineering design tools are not suitable for intensive creativity (Robertson, Walther, & Radcliffe, 2007) and do not give them the possibility to work on their principal innovative capabilities, aesthetics and meaning. **Industrial designers seem to be trapped between two types of tools they need to use none of which were made for them**.

4.2 Paperless design; significant consequences for some practitioners

We can now better understand why industrial designers suffer from a lack of adapted tools for their needs that are also seamlessly integrated with engineering design tools. This radical change was also promoted in the industry as a "going paperless" with both design and marketing objectives (Sabbagh, 1996). This signs the progressive disappearing of the draftsmen and of the hand drawing techniques in the industry.

In the middle 90's 3D CAD technology began to be competitive with traditional methods in other fields. After years of confinement in the automotive and aircraft industries it was becoming possible to economically design kitchenware and other domestic products with complex 3D shapes using a computer. This capacity was brought by the increasing number of CAD software and the democratization of personal computers, now powerful enough to run 3D software for a modest price. The product SolidWorks harvests a great part of this new market. At its release in 1993 it offers for a limited cost (compared to other CAD software) the access to industrial product design for most of the everyday objects (such as electronics, apparel, packaging, etc…). The high-end competitors such as CATIA reached their growth by incorporating more functions to their products. This lead to CAD tools with the capacity to manage the whole design process and the data it produced, from the design of factory, to the management of spare parts and assembly and maintenance operations. The PLM/PDM (Product Lifecycle Management/Product Data Management) is now an imperative for the CAD software design companies, making paper even scarcer. The disappearing of the traditional media was seen as a blessing for most of the managers but the design techniques associated, such as very intensive creativity phases, were very much challenged.

4.2 The full digital mock-up; significant consequences for some practitioners

This tendency also wiped out the physical mock-up usage. It gave very hard time for the industrial designers who were used to work on them, especially in the automotive industry where they interfere at the early design steps. ID are specialized in the rapid evaluation of shapes and their aesthetical qualities and when they studied curves on a full size drawing or mock-up they could visually detect shape defects such as curvature breaks, unwanted inflections, etc. As the design process moved away from the drawing board and into computer screens, this visual inspection process was not feasible any more since the scaled down display offered by the computer did not allow detecting shape imperfections in a direct way and did not have the capacity to represent full scale objects. Lacking these tools, industrial designers were forced to adopt engineering design tools that were not made for them. Engineers' tools were based on calculus methods to display the curves properties for the evaluation of the surfaces. They offer hardly the possibility to explore new concepts and shapes and even less the capacity to quickly represent their concepts with eye candy images.

5 CONCLUSION

From the previous sections we can conclude and start answering the question: why ID still are in search for digital tools made for them and which fit their means of action on the products they participate to design. Their needs (section 4) could be partially addressed by the engineering software (section 2) which give them direct entry doors to the manufacturing and industrial environment. They are also in need for some of the abilities addressed by the artistic software (section 3) but what they really crave for is a clever combination of both of these worlds and more than simply an addition. The compatibility of the generated models seems to be the major issue, but moreover their holistic approach of the under design products requires holistic tools. Some software seems to throw a great deal of efforts in this direction (Arrighi, Le Masson, Weil 2012) by providing them new software specifically build for them with specific capacities, being able to simultaneously granting them an integration inside the industrial design process by providing them tools inside industrial CAD environments with properties issued from the artistic world such as subdivision control and high-end rendering capacities. These game changers are directing what could be a spectrum of answers for adressing a nearly 50 years old issue. The whole new challenge stays in their design and how to pick the particular and specific capacities they require.

We propose in a future work to investigate more deeply the specific properties of the two archetypal type of software in use form a computer science and design theory point of view.

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