"Learning by Doing" Integrated Project Design in a Master Program on Product and Industrial Design

Ângela Gomes, Bárbara Rangel, Vitor Carneiro and Jorge Lino

Abstract The Master in Product and Industrial Design (MDIP) of the University of Porto, hosted by the Faculty of Fine Arts (FBAUP) and the Faculty of Engineering (FEUP), has in its genetic code the project-based learning model. Giving the students a design studio scenario, the curriculum is developed under the integrated project design thinking, taking advantage of the knowledge provided by the two scientific areas. In a straight connection with the industry, the projects are developed in a real context, for real clients thus simulating all the tasks and stages undertaken in a design company. At the end of each exercise, the best students' concepts are developed together with the industry in response to the market need, which is a job experience opportunity in the partner company. This "formula" has been a key factor for the success of both the course and the students' career. They have the opportunity to see their project executed and implemented in the market, as well as the chance for a job opportunity in their future. In this chapter, the methodology is presented followed by the course and one example of these projects: the development of school furniture and technologies for an education company, Nautilus; this project entailed the development of a low-cost stackable and evolutionary school chair for children between 6 and 10 years old.

Keywords Integrated project design · Industrial design · Project-based learning

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1 Introduction—Integrated Project Design

The growing expertise generated by the constant advances in science and technology is, without doubt, an asset [1]. However, this has led man to perceive the world as disconnected parts [2], where knowing a lot of a small fraction is the result of a shattered intelligence [3]. The expert possesses a more in-depth knowledge about less subjects [3] whereas, in turn, the designer, such as the architect, has a wider knowledge about the problem, looking for an integrated answer [4].

In the attempt to understand design, common sense invokes the preconception that it is only restricted to aesthetics, the image [5], as if it were just a simple exercise of makeup. Design, in its essence, is interdisciplinary by nature [3, 5]. This interdisciplinary vocation is present since it works together with other disciplines/areas of knowledge during design activity, which involves, beyond doubt, very different areas of knowledge and multiple socio-technological dimensions [6–8]. Therefore, it is not surprising that a designer wanders through areas of knowledge that, at a first glimpse, would not concern him [3].

Design should not be characterized as a single discipline, but as one that can be enhanced through a variety of experiences for a wide and interdisciplinary understanding [5]. The interdisciplinary nature suggests doing something that cannot be done individually nor initiated by a single subject [9]. Unlike the multidisciplinary, where multiple disciplines are employed both in a sequential or juxtaposed mode [3, 5, 10], the interdisciplinarity aims to ensure the construction of knowledge through the transference of methods from one discipline to another [10] and, as a last resort, to break the boundaries among disciplines [11], where integration and interaction among the various areas are necessary and desirable [3, 11, 12]. This is in line with the holistic concept in which the knowledge is considered as a whole [3, 11] and where the whole is more important than the sum of its parts. Thus, the contribution of various disciplines is highly valued, indicating design as an interdisciplinary area [5] where the projects claim an interdisciplinary vision [3].

The way how products are produced has been constantly evolving, and in the recent decades, there has been a rapid growth [13], in part by consumer demand for products with better quality, lower price, better performance, and smaller delivery deadlines [14, 15]. As a result, the market requires changes in how industrial designers, engineers, and production specialists develop products [14]. Design is more and more the interface among distinct areas, attenuating the frontiers of knowledge [12], requiring a focus on research and interdisciplinary interaction through teams composed by individuals from various disciplines/areas, enhancing the lateral thinking and new methodologies more appropriate to the context in which they live. Thus, crossing information among the various areas is fundamental and inevitable for a coherent and integrated answer [1, 13]. Besides, interdisciplinarity does not mean the refusal of specialization, but rather a constant questioning to the knowledge established by it [3].

Like the response to the current requirements imposes an increasing specialization in various areas [1], new production technologies have been emerging such as additive manufacturing and new CAD software, supporting the design process and increasing the productivity, while also improving the procedures for validation and optimization of digital processes through simulation and physical models for testing and validation of concepts [16, 17]. However, they are just tools requiring a methodology to aggregate them, such as the integrated project, in the same way that in construction cement is the unifying element.

Design is not, and should not be, a simple cosmetic exercise or an individual and isolated exercise, because its interdisciplinary nature suggests doing something that cannot be done individually and is not initiated by a single subject [9]. Therefore, besides considering the user's needs and constraints of the project, it is up to the design and designer the implementation of project methodologies and knowledge from other areas, such as ergonomics, anthropology, mechanical and materials engineering, semiotics, simultaneously leading the product to a better result [3, 5, 13]. This should be always done accompanied by a team composed by the most diverse areas, promoting an integrated project. Design must always be guided by a holistic and integrative vision [1, 3, 18, 19].

To sum up, it is possible to ask what can we gain from interdisciplinarity in design?

(a) Collaboration among different areas;
(b) Acquiring new knowledge through the intersection of knowledge among areas/disciplines;
(c) Inclusiveness, all have a vital role and something to say;
(d) Dealing with uncertainty, by avoiding take decisions based on wrong or incomplete information;
(e) Definition and framing of the problems. Most problems can only be understood when seen on common panorama among various areas [10, 18].

The goal of the integrated project is to transform a concept into a product in such way that the products design and the results of the corresponding processes evolve to minimum cost and high profitability quality product, shorter introduction of the product on the market, and lower cost of development [13, 20], responding to the new needs of consumers/users in a systematic and cohesive way, based on information from various areas. This breaking of barriers, for example, between design and production, is the fundamental key of this methodology, whose benefits include accelerating the resolution of problems during the project, where potential problems and bottlenecks are early identified and possible delays are addressed [21].

Despite the uncertainty about the impact of its applicability, many companies and sectors have successfully implemented the integrated project since its beginning in the 1990s [22], verifying, however, resistance, and reluctance to implement it [18]. At IDEO, an international company of design and innovation consulting, and a pioneer in the concurrent engineering in design [23], the myth of the solitary genius affects the company's efforts in innovation and creativity. The teams, which are at the heart of the entire process, are composed by elements of several different areas such as electrical and mechanical engineering, industrial design, ergonomics, cognitive psychology, and information technologies, which, together, are working for the same goal. At Virgin Atlantic Airways, the development phase of the project involves a series of meetings with the manufacturers to present the project and have their feedback. At Whirlpool, the innovation process and product development start on Platform Studio, where designers, experts of advanced production processes, and engineers work together to reflect on new trends and products, ending with a prototype for testing with users. At Xerox, designers, despite their experience in production, evaluate along with other specialists what is possible from an engineering and development perspective. It is still common for designers to follow engineers in customer visits to observe how these interact with the product during its use [21].

Concurrent engineering [14, 22–24], collaborative engineering [25, 26], collaborative design [17], collaborative engineering design [27], integrated design process [13, 18], integrated product development [24], and integrated project delivery [28] are some of the designations assigned to the same methodology. Despite the different names, they all have the same goal: the search for coherent solutions through interdisciplinary teams, which requires everyone to work compulsorily together from an early stage, in a constant and inclusive dialogue. It is like an orchestra where everyone is focused and linked to a shared goal [29]. No one can be excluded and everyone speaks a common language, regardless of their own language [13].

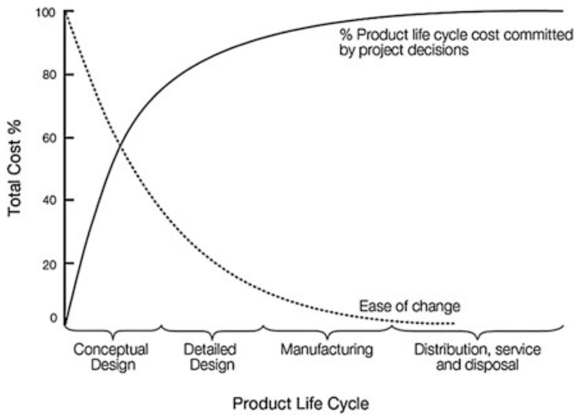
According to Dekkers et al. [22], the research on this topic—integrated project/process—highlights the importance of coordination and interdisciplinary collaboration and the advantages associated were well understood, both in academic literature and in practice, demonstrating a direct and positive effect on product innovation. The role of CAD software is extremely important and well recognized in the implementation of the integrated project [15, 22, 23, 30, 31], since without it the management capabilities of a large amount of data and information would be strangled and difficult.

Unlike traditional development processes, more time is allocated in the initial phase of the project to avoid correction of mistaken assumptions at a later stage of the process, where the opportunity to make changes decreases significantly and costs for changes increase exponentially with the advancement of the process [13, 18, 32] (Fig. 1).

Although there is no single definition for integrated project, this concept differs in intention and emphasis [18] from the conventional design process in the following aspects, which can be an asset to the project methodology in design:

Goal-driven: The goals and objectives are defined as a means to an end where those involved must demonstrate commitment instead of compliance [13, 18];
Clear Decision Making: Problem solving and decision making are based on information from different sources and areas [13, 18];
Team leader: someone responsible for the design process [13, 31];

Fig. 1 Importance of decisions in the earlier stages of product development (adapted from [32])



Inclusive/Collaborative: Everyone, since the client to the operator, has something important to contribute to the improvement of the function and/or performance of the product. The designer is not the "form-giver" [18], but an active participant in exploring ideas within an interdisciplinary team where everyone plays an active role since the beginning of the process and where the trust is a fundamental pillar [1, 18, 33];
Integrated: The holistic thinking is a constant where the whole is greater than the sum of its parts [1, 4, 18]. The isolated development of the components leads to worse results for the entire system, because they tend to work against each other [19];
Interactive: On the integrated project design phases are cyclical and interactive, and not linearly and sequentially as in the traditional design process (Fig. 2);
Competitive Advantage: Once it is capable of producing products with better quality and lower costs, it will be ahead of the competition.

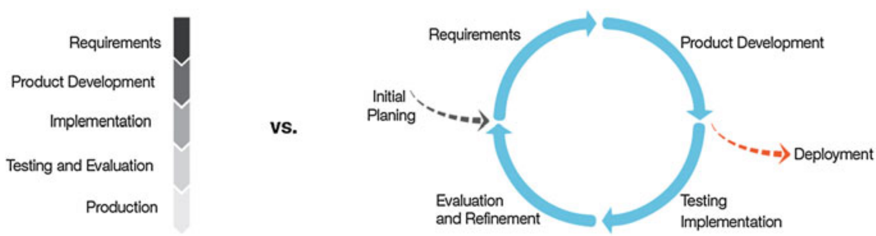


Fig. 2 Traditional sequential development method (left) versus integrated project method (right)

2 Interdisciplinarity in Design

Interdisciplinarity is defined as a methodology of knowledge integration from two or more disciplines, and depending on the capacity for dialogue and exchange between different teams, so that the work of each one is mutually enriched by the other [3, 10]. On this basis, the decision process is constantly fed by the validation of other areas, thus allowing to deepen the level of detail of the project within each area. Contrary to usual project methodologies, multidisciplinary would rule out the idea of a fragmented knowledge, scattered into diverse areas, which often prevents a link between parts and the whole [3, 33]. To achieve that complicity in different fields of study, the decisions are complemented not only by the identification of knowledge from other disciplines but also through ownership of such knowledge, i.e., through mutual combination of such knowledge thereby taking joint decisions that are built on sound technological basis [3, 33].

As Couto, cited by Fontoura [3], asserts, interdisciplinary implies "(…) a change of attitude, which allows the individual to the limits of own knowledge in order to be receptive to contributions from other disciplines. Interdisciplinarity must therefore be understood primarily as an attitude, driven by a rupture with the positivistic fragmentation-based approach, with a view to ensure a broader understanding of reality. This approach only facilitates an effective interaction that is considered a synonym of interdisciplinarity."

Reginaldo and Baldessar [5] consider design as a field of study "without specific boundaries or defined area" and "buildup of knowledge and skills borrowed from different fields, and using a series of flexible and adjustable models that are applicable to any time and circumstances," thus in need to constantly seek innovative design methodologies. Due to the fact that it produces and applies knowledge [3], the field of design is bound to acquire knowledge specific to other areas. Engineering, ergonomics, anthropometry, and material science altogether [3, 5, 34] contribute to solving a problem, provide the answer to a specific question, or contribute to generating new ideas [10]. Nowadays, designers try to integrate the scientific methods of those areas into the design development process [35].

Globalization of markets intensifies competition and puts pressure on designers to adhere to interdisciplinarity methods as, in such a competitive context, it is no longer possible to use solely the traditional subjective and emotional methods of design [35, 36]. Currently, it is impossible to design in isolation, as no individual knows enough about the relevant disciplines that make a project a success [35, 36]. According to Bürdek [35], referring Lutz Göbel (1992) "(…) companies increasingly need neither specialists (people who know a lot about a little), nor generalists (people who know a little about a lot) but rather integralists (people who have a good overview of various disciplines with deeper knowledge in at least one area). These people must be especially capable of thinking about and acting on issues in their entirety."

According to Fontoura [3], this implies an interaction between concepts and methodologies. The interaction of concepts or the reciprocal exchange of practical and theoretical knowledge between ranges of disciplines is the basis for the area of design. The design process may be influenced by several external factors, such as the market, technologies, investment, environment, thus resulting in interventions from different fields in the development process of the project, as explained by Ashby and Johnson [37]. Ulrich (2010) referred by Bleuzé et al. [38] defines, "(…) the architecture of an artefact is more precisely as (1) the arrangement of functional elements; (2) the mapping from functional elements to components; and (3) the specification of the interfaces among interacting components."

The interaction of concepts or the reciprocal exchange of practical and theoretical knowledge between ranges of disciplines is the basis for the area of design. The design process may be influenced by several external factors, such as the market, technologies, investment, environment, etc, resulting in interventions from different fields in the development process of the project, as explained by [39]. In order to create a product, appropriate choice of materials has to be made; hence, knowledge in the area of material sciences is required [37]. The development of a product may benefit from different areas of engineering, such as chemical, electrical, production, food, or mechanical. This interaction between engineering and design will allow for better results in terms of mechanical and operational performance, costs, and durability of products [6, 34, 37].

The methodological interaction combines approaches of diverse disciplines, thus creating a common strategy to achieve more comprehensive and rigorous final results. However, to ensure the methodological or conceptual interaction, all actors in the process shall articulate their own work processes [34, 37, 40–43]. Any project development process, in any area, includes three main stages:

Definition of the problem: describes the purpose and the main objectives to be achieved [37], by creating a new product that matches the specific needs of the users and brings advantages as compared to existing competing products [42];
Definition of concepts: Ideas are proposed to meet the objectives taking into account the technical and aesthetic requirements [37];
Development: At this stage, the project is developed, from its initiation [42] and design of specifications for each component, to testing of the various components, in order to optimize the product as a whole, increasing their performance and analyzing the underlying costs [37].

Cross [34] also defines this method as a heuristic process, since designers use previous experience, general guidelines, and golden rules to define the most appropriate direction, despite not guaranteeing its success.

Currently, the process of design follows sequential tasks carried out with various tools [40, 41, 43] and allows the designer to pose questions and to seek the solutions to the problems encountered [6, 40, 44]. As it is a linear process that only allows to proceed into the next step when the previous one is concluded, is often necessary to go back to solve problems not initially detected. For this reason, some authors define the process of product development not just as a linear method but also as a straight-line method with iterative cycles [6, 40, 41]. The effectiveness of these iterative cycles is reinforced by common methodologies adopted by actors from the different disciplines. For instance, SolidWorks is used by designers but also by mechanical engineers, who use this program for numerical modeling of shapes. Also, designers use CES EduPack (Granta Design, Cambridge) to select the most appropriate materials in a sustained, technical and scientific manner. Engineering defines the concepts by analogy to previous cases, since it concentrates mainly on the functioning of products, by giving emphasis to the effectiveness of the mechanism adopted [36, 45–48].

The principle adopted is based on the use of a tool of creativity, usually designed as approach called by analogy or "design fixation," and often used intuitively by engineers and by designers [48, 49]. The analogies approach is based on the parallelism established between two products from different domains [46, 47, 50], in an explicit or implicit manner that may facilitate the adaptation or creation of new products [48, 49]. As stated by Evans [51] "design, a human activity, is discovery; it is discovery of existing but as yet undiscovered ideas."

The analogies approach allows applying the existing knowledge in a different context, thus improving the quality of the proposed solutions [46, 47, 52]. This approach is consistently based on the relational and functional similarities between the product source and the objective [40] and may take various forms. Also, analogies may be observed directly when looking into comparable situations, when the person integrates the problem while looking for the solution, when using natural elements that are similar to the problem to solve, and finally using fantasy or imagination to solve the problem as a fairy tale. Designers and engineers make use of analogies when creating new products. To invent the concept of desktop, Steve Jobs made a direct analogy with his desk where he had access to the bin, the folders, and documents. For instance, Word is similar to handwriting in a blank page where words are added in order to produce a text [50].

3 Integrated Project Design as Methodology in MDIP, a Case of Complicity Between University and Industry

Universities finally realized that it is important to train professionals instead of just researchers. When they finish their carrier, most of them enter the labor market, and only few stay in the university or in research centers. During their training, it is important to give the students this perception. Working in real context is, therefore, fundamental to train to the labor market needs [53].

Nowadays, the complex industry panorama confirms the need for interdisciplinarity, at a professional and scientific level. Efficiency of the production processes and the performance of the products are demanded in all areas of activity. Knowledge is no longer organized into different shelves, and all disciplines have to contribute to the efficiency of the product. The team is getting larger: Besides designers and engineers, end users, and industrial technicians are fundamental to optimize all the product development. The need to open the academy to the industry reality has been changing the teaching pedagogy in some courses related to engineering [54–57]. In Civil Engineering courses at the same Faculty, this experience has been led with second-year students [58]. Bringing this reality to the university has been a priority in MDIP, at FEUP, developing projects in a real context. Learning by doing is a methodology where the participants, students, teachers, and “clients” discover new paths to achieve a solution. Introducing concrete cases with real “clients” intends to establish a relation between these two worlds, allowing the student to perceive the problems in the “reality” [6]. Students are given the opportunity to communicate directly with companies and understand the production systems. Companies can develop ideas of problems, which is not possible in the daily life. This direct relation with real problems results in extra motivation and dedication to the possibility of job offers or having the projects implemented in the market.

The Master Program in Product and Industrial Design (MDIP) of University of Porto is a project-based learning (PBL) course. The training is based on unifying Courses of Project, where students, under the workshop frame (extended stay in school that can go up to 40 h/week, between tutorial hours and individual work) successively develop several products, a process in which other teachers from converging courses also participate, reflecting the aspects that relate to their subjects. The evaluation of these courses takes into account a portion resulting from the application of knowledge acquired to the projects developed [54].

Each project has the cooperation of a partner company or other external entity that launches, monitors, and validates the obtained results, without participating in the assessment, which is sole responsibility of the Faculties.

This commitment stems from the understanding that the design of new products, from capital goods to consumption ones, the so-called tradable goods, is a cooperative project-oriented business that must emerge from the intersection of three cultures: engineering, design, and management. Figure 3 shows this cooperative vision of the course [54].

Students visit companies’ facilities and have contact with manufacturing processes and installed capacities. The companies present them their market and more relevant needs. During the project (held at FEUP and FBAUP), companies’ technicians monitored, twice, the results under development. At the end of each semester, a public presentation of the work is made, in some cases in the partner company. If the company is interested in one or more projects, an agreement is made to the industrialization of the products.

In MDIP, this connection between the reality of the labor market and the scientific research has been the motor of its success. The practical cases are developed with the industry in a partnership association.

The students that start this course are, in its majority, designers trained in bachelor courses, and some mechanical, electrical or industrial engineers, or architects trained in integrated masters courses. In their previous courses, they were used to work with projects, but most of them without a specific client and with no possibility to be realized. Each year, in the first day meetings, new students refer

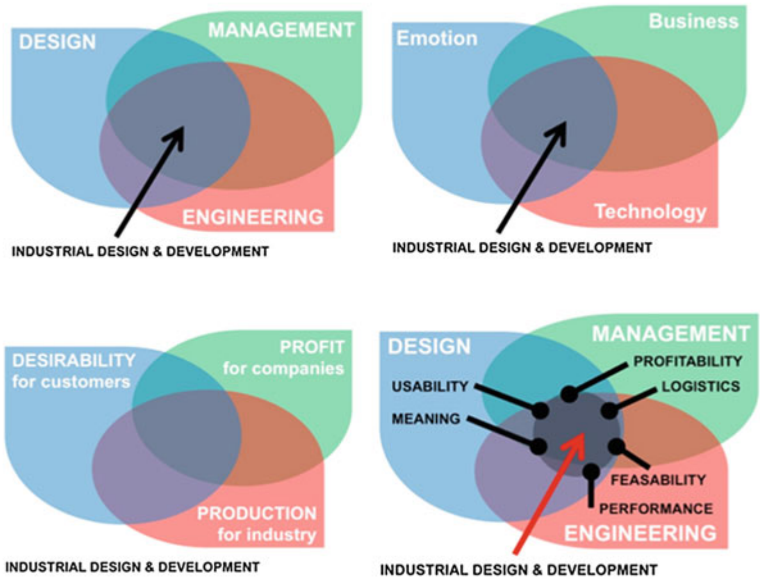


Fig. 3 Overview of cooperative industrial design and development [54]

that the choice of coming to this course is due to the possibility of having their projects realized as well as with the job opportunity that this methodology offers. Since the beginning, students know that their effort and their professional capacity will be fundamental to achieve their expectations.

The scenario that is presented to the students is equal the one that they would have in a design studio, or an industry. They are organized into teams to develop different solutions for the same program that will compete in the final presentation for the client.

The fact this course is a partnership of both the Faculty of Engineering and the Faculty of Fine Arts provides the students with different approaches and makes them understand the meaning of integrated project design (IPD). The different disciplines feed the project that is developed in the design studio disciplines. Once again, the real scenario is presented; they search for the technological answers in the related discipline with the specialized teacher.

After the first year, students can develop the selected projects by the client and the teachers, as a research problem for their one-year master thesis. They are asked to improve their projects making a scientific research, increasing the state of art related to the technical and scientific issues and performing a set of experiments to find the solution to industrialize the concept they have created in the first year. In this second year, the scenario is close to that of an industry research center in the University workshops and laboratories. Like the professional practice, they prepare their projects in an integrated project design (IPD) thinking, developed with teachers with different backgrounds, designers, architects and mechanical engineers. After this phase of research, students go to the companies or industries to improve the project in a professional stage program, until its industrialization.

Some of the projects developed in the past years are now in the industries and in the commercial market. A glove for motorcyclists is now in the final phase of the industrial process. An evolutionary chair for children between 6 and 10 years old is now in the market. The primary schools from the municipality of Penafiel are today using the Dual-Step chair. The research made, searching for a universal chair, was recently published in Applied Ergonomics [59], which demonstrates the quality of the work that has been done.

After these two years, students realize the different tasks involved in the career that they chose, in both the professional or scientific paths. They learn, by doing, that all the disciplines involved in the production of an item, have to work together to achieve an integrated solution that responds to nowadays strict requirements.

4 Case Study—Developing an Evolutionary Chair for Children Between 6 and 10 Years Old

In this chapter, an example of these exercises, developed in the two years of the course with Nautilus Company, is presented; the development of an evolutionary chair for children between 6 and 10 years old. The concept was created during the first year in a teamwork and in straight collaboration with the company. During the second year, after a deep scientific research on the ergonomics issues involved, two of the students had a professional experience in the company, developing the projects in industrial context. One of those chairs is now in the company catalogue and already in use in some primary schools. At this moment, one of the students is already part of the company staff.

Like other companies that collaborate with MDIP, Nautilus, a Portuguese company specialized in school furniture and education technology, asked in the first meeting with the teachers to solve a problem that they had for a long time. The proposal was the development of a school chair for primary education, particularly for children from 6 to 10 years old, which should be adjustable in height, stackable and with a low production cost. It was a problem that they wanted to solve, but in the day-by-day life there was never time to think about it. Finding a solution for a universal chair would deeply optimize all the company chairs manufacturing process. There would be just one size of chair, one cast in the production, one type of stock, one type of order.

In the first year, the concept was defined in teams with distinct backgrounds, designers, and mechanical engineers. During the first week, the students visited the different factories of the company and perceived the available technologies. Similar to a design studio context, the teams proposed different ideas to the same problem. After some weeks of work in the Design Studio of FEUP, the first ideas were presented to the company to validate the concept proposed. In the second part of the exercise, each student should develop the concept in detail until the execution project scale. At this phase, being in the Faculty of Engineering was crucial. The students easily found the information on the specifics issues that were arising with the teachers of different areas, design, ergonomics, mechanical engineering, etc. Although they were developing individual proposals, they worked as a team, helping each other. The mechanical engineer students helped the designers to study the mechanical behavior of the solutions in SolidWorks. The designers helped the mechanical engineers to prepare their presentations with InDesign or Photoshop. The students with an Engineering background helped in the definition of the mechanical details. The students with a design background helped in the aesthetic of the product. It was a real collaborative work, like in the integrated project teams. Meanwhile, when they had specific problems related to the manufacturing process of their solutions, the company was always available to help.

At the end of this first year, the final presentation was made for the company. Students prepared their individual projects as if they were in a competition. The company would choose one or two ideas to be industrially developed in the following year. The presentations were very professional, each one made a short movie of the proposal, explaining the production system and the use of the product, a poster communicating the idea, a marketing flyer, a folder with the drawings details and specific information, besides a small-scale 3D-printed chair prototype. The CEO of the company was surprised with the quality of proposals and instead of choosing one he selected two proposals.

In the second year, two students developed the selected projects. In a first phase in the Faculty, exploring the ergonomic issues concerned with the universal chair, and in a second phase redesigning their projects to make them industrialized. A detailed research on the design of the universal chair was conducted with the teachers [59].

After two months, the students went four days a week to work in the company, and once a week they met with the teachers to report the development of the project. They went through the various phases of production; the redesign, the preparation of production, the production set, the validation, and the implementation. Now, they can see one of the products being used by primary school students in a small city close to Porto and the product already in the catalogue of the company.

In this chapter the result of three of these projects is presented, two of them developed in the second phase of the exercise, with the company in an industrial context.

4.1 Three Concepts, Three Solutions, Two Research Problems

Of all the projects developed, three adopted the integrated project as the working methodology. Unlike a current design process, the starting point for the solution to be developed was defined by the mechanical behavior of the chair and regulation system. The projects were of high technical and scientific consistency and as a result were selected by the company to be developed in a business environment with the purpose of its production and commercialization.

In project A, from student Vitor Carneiro, the starting point was defined by the mechanical behavior of the chair, determined in part by the concept adopted, in order to develop the final solution. As such, a convergence among form, regulatory mechanism, and material was paramount and the focal point in the development of the solution, where the need to use engineering tools, such as CAD software and material selection methodologies, would allow a support and a more sustained justification of the solution adopted than only based on aesthetic and formal criteria. Throughout the entire development process, everything has been accomplished, designed, and conceived in an integrated environment where partial and complete simulations have been done continuously in order to achieve a valid and justified solution in several parameters.

Project B, developed by the student Ângela Gomes, began by exploring the mechanical response to the problem under study. Finding the concept of interdisciplinarity based on two essential premises, interaction between concepts and interaction between methodologies, engineering concepts were used, more specifically those related to the mechanisms, in order to solve the height adjustment problem of the chair, while also ensuring that it was stackable. She applied a methodology of product development learned in one of the curricular units (CU) of the course. This method consisted in the search for mechanisms of regulation, even if they were not used with the purpose of regulating height. After researching the existing mechanisms, she tried to perceive the functioning of each one, disassembling them and analyzing how the various components were related.

The methodology used in the project is based on the method of product creation adopted by engineering. This method is based on the use of a creativity tool called by analogy, usually used in an intuitive way, both by engineers and by designers [48, 49]. Analogies are based on the parallelism created between two products with different domains [46, 47, 50], allowing to apply existing knowledge to another context, thus improving the quality of solutions [46, 47, 52]. By always ensuring the principle of the relational and functional similarity between the source product and the objective [40], analogies can take several forms. After the chair was developed, a direct analogy was used, since for the generation of the mechanism a search of several existing mechanisms was made, selecting next those that would be the most suitable for the type of regulation that was intended, making adaptations of the same to the context in which they would be applied.

In project C, initially developed by student Maria João Pato and later by Vitor Carneiro, introduces a radical innovation in the market of adjustable school chairs by exploring an existing lack, but quite evidenced by the literature: the lack of regulation of the depth of the chair. As vital as the height of the chair of the chair is the depth of it, so the starting point in this project was defined by the development of a system capable of simultaneously adjusting the height and depth of the chair, without thereby compromising the stacking of the chair, and its low production cost.

In all the three projects, the starting point focused on research of the state of the art, legislation, standards, materials, adjustable mechanisms, and user needs. It was observed that:

(a) From the existing school chairs, only a tiny number conciliated the requirements of stacking and regulation of chair height;
(b) From the adjustable chairs in the market, the chair adjustment was always made step by step and mostly using the pin mechanism (Fig. 4);
(c) Stacking the chair does not have the same meaning for the companies as for the school. From the companies' point of view, stacking is about promoting less storage space and a larger number of chairs per load in transport—vertical stacking. From school point of view, vertical stacking is not a daily necessity as opposed to lateral stacking. For daily cleaning of the classrooms what matters to schools is that the chairs can be placed lying on the table and stacked laterally promoting efficiency and speed;
(d) It is very common that in the same classroom the chairs are the same size mark, which is not the best option. It was found that within the same class there can be differences of 200 mm between the lowest and the highest students;
(e) The use of school furniture not suitable for its users is enhanced for bad postures, which have a direct influence not only in its correct and normal growth, but also in their cognitive development [60–65].

Given the aforementioned observations, it was defined, as design principles, a continuous adjustment of the chair rather than step by step; the student should be able to regulate the chair itself; the chair should be stackable; and physical lightness and aesthetics should be present. Given these facts, it is more than evident the need for an integrated project where three main disciplines prevail; design, ergonomics and engineering, especially when the need to combine stacking and continuous regulation of the chair seat have made focus the development of the concept in a strategic alliance, almost like a game of balance between form and mechanism, design and engineering, finding a viable and valid solution (Fig. 5).

A continuous and simultaneous focus on the mechanism, in the shape and taking into account users' needs and requirements were essential to the project. This interaction between design and engineering, working together to achieve the

Fig. 4 Pin mechanism

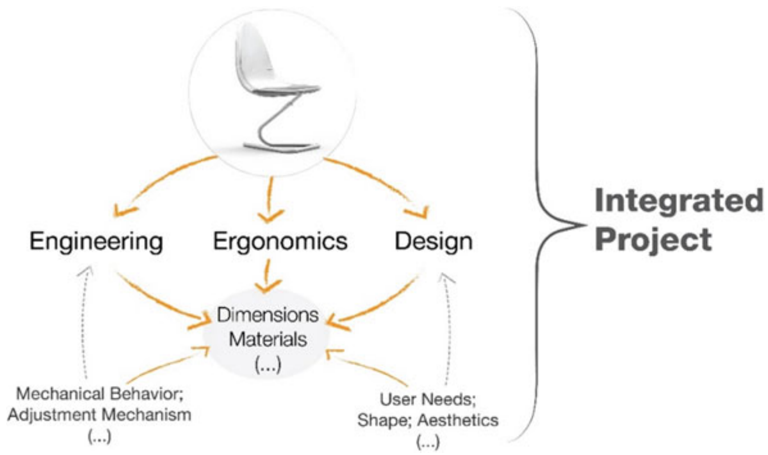


Fig. 5 Contribution of different areas for the school chair development under the integrated project methodology

optimal parameters in the definition of the product, can start from a simple communication of ideas until the interaction of concepts.

Once the project requirements were outlined, the students' proposals followed different paths, always accompanied and validated by teachers with different skills and company technicians.

4.1.1 Project A: Clamp Chair

In the pursuit for a chair that would allow a closer dimensional of the anthropometric user needs, the definition of design concept emerged from the principle of a continuous regulation and, because of usability issues, in one place which presupposed the convergence of the various support points of the chair to only one. The chair development assumed a convergence between form and mechanism. To achieve it, it was essential to understand the mechanical behavior of the chair and to focus in the solution development, where the need for engineering tools, such as CAD software, would allow a stronger justification of the adopted solution than just based on design criteria.

The most promising concept emerged from a strong mechanical component combined with mechanism's simplicity in which the materials would have a key role to play. With a Z shape and composed by two distinct parts, the structure and the shell, the adjustment is accomplished by telescopic tubes, which make up the structure, and its position lock/unlock is performed through a single system, the same used in bicycles seat, which allows a comfortable and easy handling and also a continuously adjust. Using a simple guide system it was ensured that there is no misalignment between the shell and the structure, thereby guaranteeing the permanent balance of the chair (Fig. 6).

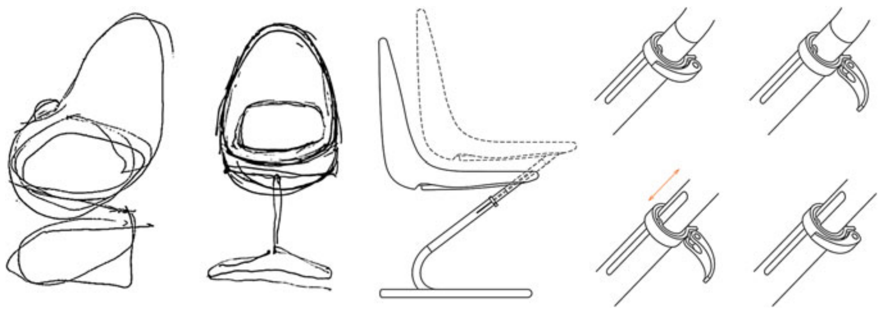


Fig. 6 Sketches of the relation between form and mechanism in the school chair design

The active participation of designers and mechanical and materials engineers (teachers, students, and company technicians) was vital to get a feedback of what be possible to achieve in terms of solutions. The need for its detail and specification, such as dimensions, materials, mechanical behavior, were evident and essential. The use of CAD software, 3D modeling, and mechanical behavior simulation were needed for a product detail.

The Right Material in the Right Place!

Nautilus uses mainly two types of materials for the development of school furniture: metal, mostly low carbon steel, and plywood. However, the thermoplastic polymers were recently included as election material, investing on the acquisition of injection molding equipment for production. Thus, and given the primary form of the concept, which divides the chair into two components, the structure and the shell, the metal and polymer were the materials family chosen for the concept development. The need to refine the choice of materials was a vehement necessity, particularly the mechanical behavior of the structure whose shape needed to be refined through simulation tests. “The right material in the right place” [24].

Screening and selection are two key steps in material’s selection process [66]. The first allows a reduction to a manageable number of materials, while the second one allows obtaining a ranking of potential materials in agreement with the established requirements. Based on a systematic methodology of selection materials through a TOPSIS analysis, considered the best method of multi-attribute decision making selection [66], a ranking of potential materials for the structure and the shell was obtained taking into account the requirements and objectives defined (Fig. 7).

Delineated the materials, the analysis of the mechanical behavior of the chair when subjected to stress was performed in order to achieve a viable solution and establish dimensions such as tube thickness. Through SolidWorks software, the 3D modeling of the chair was carried out and, subsequently, the static simulation tests to the structure and the shell to make any necessary corrections and improvements. A behavioral analysis of the structure and the shell assembled was performed

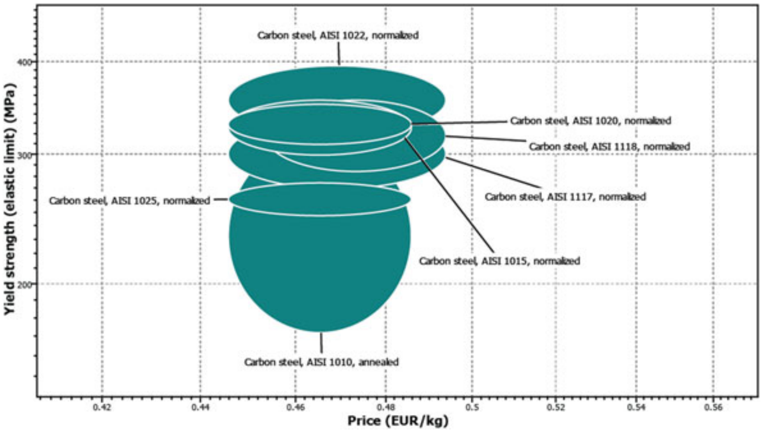


Fig. 7 Yield strength versus price for different types for construction steels (CES Edupack software)

afterward, since the behavior of the set would effectively be slightly different from the individualized behavior. The tests were performed in SolidWorks, through the simulation application (Fig. 8).

Through the improvement of the form and the constructive solutions, it was possible to decrease the nodal stress (von Mises), and resulting critical strain, in the various static simulation tests conducted to the structure. This is a cyclic cooperation between design and engineering, or “functional design and industrial design” [26], in a single design process where both evolve in a way that they are influenced by each other and in which the sketch is a constant tool for refining ideas and facilitating problem solving [6] (Fig. 9).

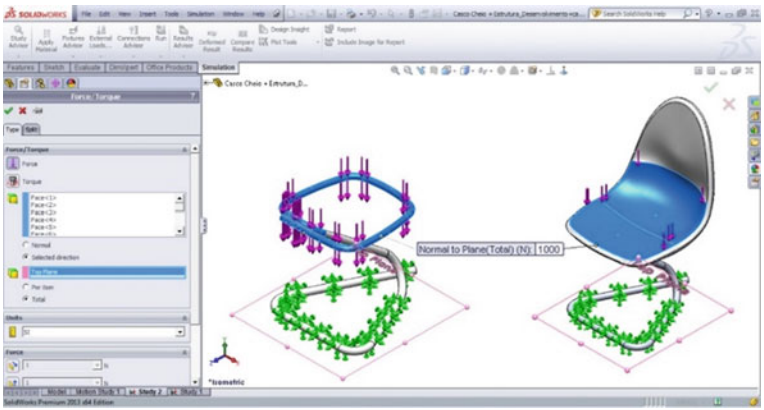


Fig. 8 Force (N) applied in the static tests

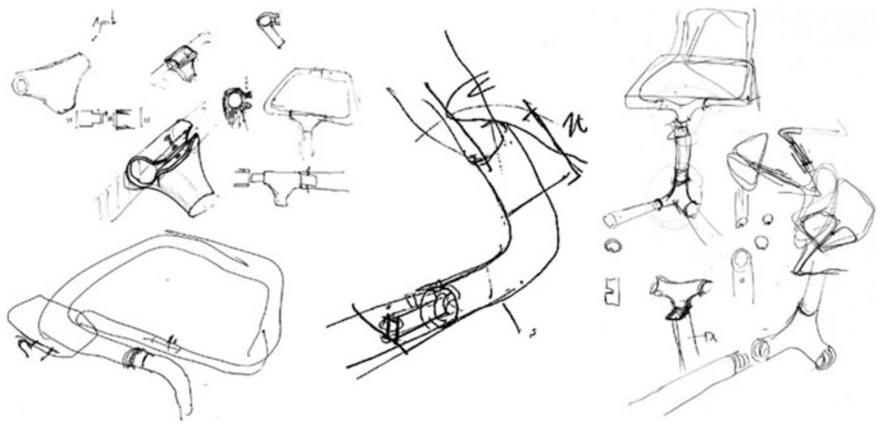


Fig. 9 Sketches for search constructive solutions and improvement

This interface between design and engineering allowed that the nodal stress in the order of 930 MPa, well above of the material yield strength, was successively decreasing until obtaining an acceptable 298 MPa. It was important to obtain the mechanical behavior of the assembled structure and shell. Everything was performed, designed and conceived in an integrated environment where partial and complete simulations were continuously made, in order to achieve a valid solution and justified on the various parameters defined during the product development phase. The result proved to be a project of high technical and scientific consistency. However, and despite the interest expressed by the company, the project turned out not to proceed to production (Fig. 10).

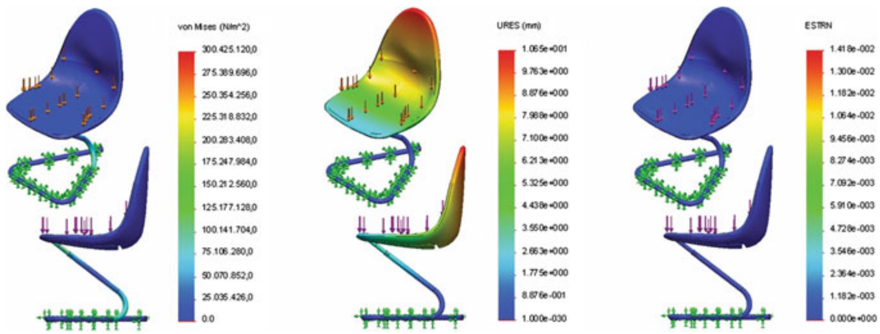


Fig. 10 Nodal stress (von Mises), displacements (URES), and equivalent strain (ESTRN) of the final structure and shell assembled (deformation scale = 1)

4.1.2 Project B: Seat and Growth Chair

One of the projects selected by the company was Seat and Growth Chair, developed by Ângela Gomes. After a deep research on the ergonomic issues concerned with the height adjustment of the seat, the student developed the prototype in the company, taking part in all the phases of the industrial process. Starting from the deep study of the mechanism, the design of the chair was developed based on solid and technologically sustainable decisions. Using a shared relationship promoted by the integrated project, it was possible to improve the product's functionalities, ascertain the quality of production, and thus enhance its creativity. Having a greater number of information about the project, the designer can solve problems in an innovative way.

The project B had as a starting point the operation of the mechanical response to the problem in study. After the research made to support the design process, the student established that to achieve the company objectives, two questions prevail:

- Is it possible to improve the usability of the adjustment mechanism without compromising its effectiveness?
- Is it possible to adapt this new mechanism to a chair developed according to the existing production processes in the company?

To answer the first question, a deep research on mechanical system was led by the student. In order to tackle the requirement that the chair would be simultaneously height-adjustable and stackable, data was gathered related to the existing mechanisms of height adjustment and the diverse stacking systems. An analysis of products for a similar purpose or products with a different purpose but similar mechanisms, offered by the main competitors in the market, was made. As the product targets the specific market niche of schools, the solution to propose should be produced and offered in the market at low costs and prices. It was therefore decided to analyze manual mechanisms of simple operation, as the use of more sophisticated technologies would increase the production costs.

Once the first drawings were finalized (Fig. 11), a few modeling tests were applied in order to check the matching of main selected concepts with the required functionalities. To validate this operation and better understand the stress resistance of the chair, the students consulted their mechanical engineering experts.

When the mechanism was selected, it was concluded that, in order to satisfy the technical requirements of the product, the concept should be submitted to additional improvements, through a systematic trial and error approach of the solutions to the problems encountered. On this basis, the iterative process resulted in the final concept design of the chair (Fig. 12).

Designed for the child to be able to adjust easily the chair, the height adjustment mechanism was inspired on the trestle system. Stacking is possible from above and up to five chairs. The seat is manufactured from wood and different colors are possible, as shown in Fig. 13. It is also suggested to apply a different color to the adjustment mechanism. The frame is manufactured from steel, selected considering its high resistance.

Fig. 11 First drawings

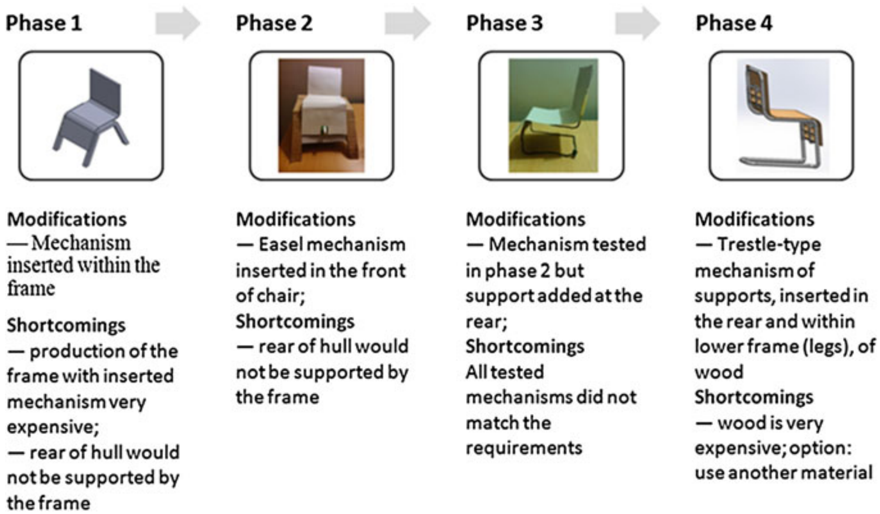


Fig. 12 Project evolution (from left to right)

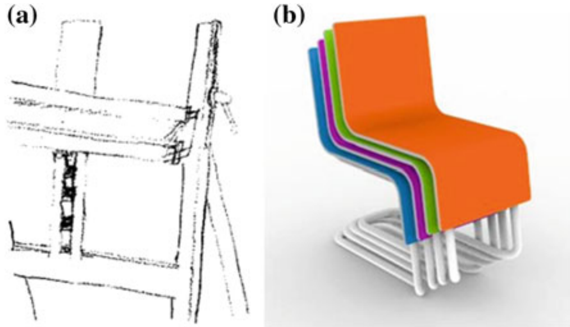


Fig. 13 **a** Adjustment system (inspiration); **b** stacking

After having the concept design of the chair, the next step was to adequate this concept to the production constraints of the company. The main corrections pointed out by the company were the method of fixing the adjustment system, the dimensions of the tube utilized and the need to consider the Standard in use to scale out the chair. In the company, the design and technical team analyzed the project and suggested a redesign of the product, to be adapted to the technologies available in their factories and with regulations Standards that they work with [67].

The next step was to adequate this concept to the production constraints of the company. Once selected the material of the different components, the definition of the production processes was made. Having the processes of the company as a starting point, the structure was produced in three steps: cut off the tubes, curving the tubes using the CNC process, and welding the different components. The seat was produced by making the plywood laminate and conforming the shape in a vacuum press available on the company (Fig. 14). The last component was the regulation system for this and having in account the material, it was decided that the best process was the milling cutter.

At the end of the production process, some prototypes were made resorting in an iterative process of testing and concept improving. The validation of the proposal was incomplete due to the fact that the chair was not completely finished, requiring some changes and testing by children and in a school environment. Besides the proposed changes, it was still necessary to reflect on the manufacturing processes of the different components of the chair, considering the costs and production times, to optimize its production (Fig. 15).

The cooperation with Nautilus was fundamental so that the concept of Seat and Grow, developed in the curricular unit of Industrial Design Project, was transferred from theory to practice. The access to the materials, technologies and manufacturing processes of the company, allowed knowing the industrial universe, helping in the decision making during the improvement of the concept. In addition to the industrial constraints, it was also possible to realize that production times influence the evolution of the development of new products.

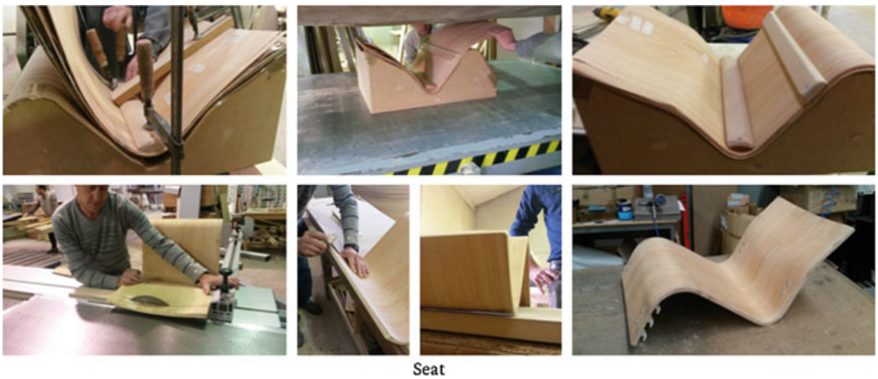


Fig. 14 Production of the seat

Fig. 15 Last prototype and some tests that were made

4.1.3 Project C: Dual_Step Chair

The second project selected by Nautilus was the Dual_Step Chair, developed by student Maria João Pato in the first phase and Vitor Carneiro in the second one. Instead of starting from a new design for the chair, Maria João Pato chose to redesign one of the company's chairs already in catalogue, the Uni_Step chair.

The objective was to find a system that could make a three-dimensional adjustment with a simple mechanical system. The intervention of teachers of different areas was fundamental to find the answer, from architects to mechanical engineers. In the classroom, the help from the other students with different background was also crucial to find the concept of this solution. After the first year, student Vitor Carneiro developed this project in his research thesis making a study on a universal chair design system and following the industrialization of this concept.

The concept of this project appears with the analysis of the European standard for the design of school furniture, EN 1729-1: 2006 [67], and the perception of dimensions variations in sizes needed to accommodate primary school children. Between size 2 and size 4, proposed by the European standard, seat height and depth may vary by 80 mm. From these requirements, it was assumed that the height of the seat had a great impact in ergonomic terms, which would explain why the height-adjustable school seats have a fixed seat depth, as was verified in the market research carried out. However, in a height-adjustable chair with a single depth, two situations may occur. If a greater depth is used, children with a smaller

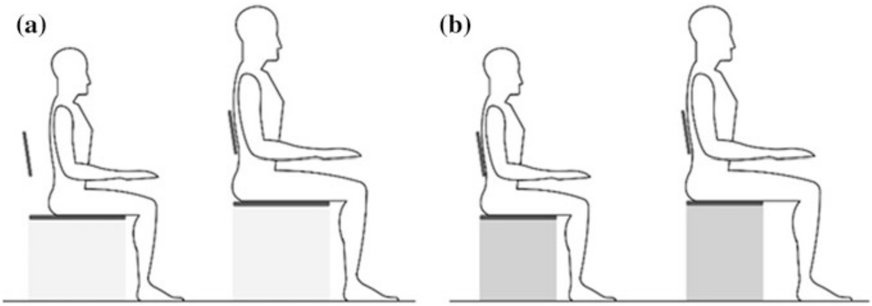


Fig. 16 Consequences of a single depth on adjustable seats: **a** adjustable seats that use a seat with greater depth means those smaller children cannot use the backrest; **b** adjustable chairs that use a seat with a lower depth leads to lack of support in the thighs in older children

gluteal-popliteal length cannot properly use the backrest (Fig. 16a). If a lower depth is used, it may lead to a lack of adequate support of the thighs in children with a greater gluteal-popliteal length (Fig. 16b).

For all this, it was decided to include another requirement for the project in order to improve the ergonomic aspects of a school seat: The height and depth of the seat should be adjustable, preferably through a single movement. The ability to change both dimensions simultaneously will allow children to learn early on what should be the correct posture when seated.

As a result of this analysis, it was necessary to move two axes simultaneously, so that small children would have the height and depth of the seat in the lowest size, and as they grow, the seat could be simultaneously adjusted to a greater height and depth (Fig. 17).

According to Zimmerman [18], in some cases the best response may not be the result of a new product, but rather add value to an existing product. In this way, and taking into account the fact that the cost of the product varies according to the materials and manufacturing processes used, it was decided to develop this chair based on the design of the Nautilus Uni_Step chair. The procedure was thus the transfer of knowledge, components, and materials (Fig. 18). With this approach,

Fig. 17 Operating diagram of the two dimensions: seat height and depth

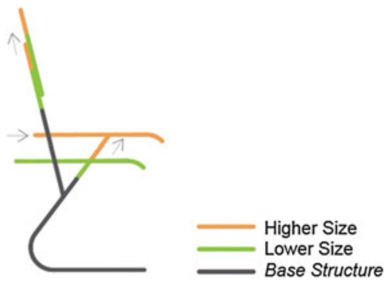


Fig. 18 Nautilus Uni_Step Chair (left) versus Dual_Step Chair concept (right)

one could combine the best of both worlds. The first two-dimensional adjustable school chair that allows achieving proper regulation with just one movement, and a quality product with low cost of production, therefore, accessible to schools.

Recognizing the innovative nature, clear benefits, and economic viability of the Dual_Step Chair, Nautilus has shown an interest in advancing with the project in a business context, integrating the student into its multidisciplinary development team. In the process of detailed design of the Dual_Step Chair, and in order to achieve an economically viable product that can be produced in the company, we worked on three fronts to achieve a technically and formally capable product. Technical solutions were developed for the mechanism of regulation and connection between the base structure, the seat structure, and the backrest structure. The improvement, testing, and validation of the locking handle of the chair position were sought. The redesign of the chair was carried out, according to the completely productive process of the company. Through sketching, 3D modeling software SolidWorks, and chair prototypes, various solutions have been developed, matured, and tested. Several chair prototypes were produced and subjected to several rigorous tests in order to guarantee the efficiency, effectiveness, safety, and quality of the chair until the final solution was reached (Fig. 19).

With the end of this research and development process, the Dual_Step Chair, the first school chair with adjustable seat height and depth, was ready to equip the first schools, making them an asset in promoting good posture practices at school (Fig. 20).

This contribution was evidenced by the Institute of Industrial Engineers (IIE) and GOErgo, which awarded the Dual_Step Chair with the Creativeness in Ergonomics Student of the Year Award, at the 18th Annual Applied Ergonomics Conference 2015 in Nashville (Fig. 21). This award recognizes achievements in the research and application of ergonomics, including process improvement, applied instrumentation, and product development.

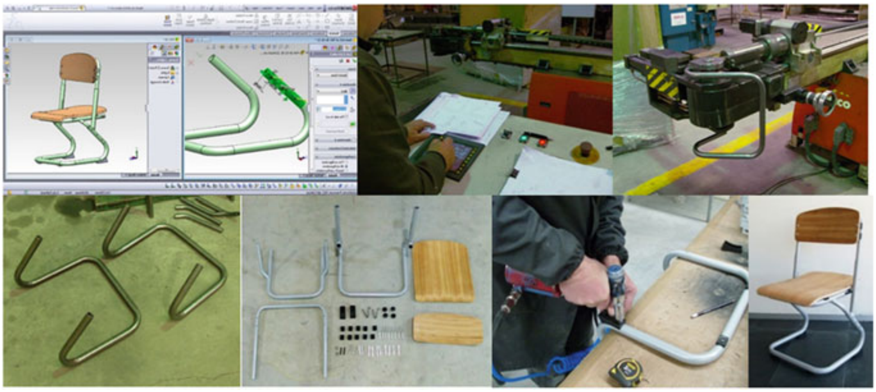


Fig. 19 Example of the production process of one of the prototypes of the Dual_Step Chair

Fig. 20 First Dual_Step Chairs equipping a classroom of the Irivo School Center

Fig. 21 Ceremony of delivery of creativeness in ergonomics student of the year award to Maria João Pato and Vitor Carneiro

5 Conclusions

The integrated project is a methodological approach with considerable advantages in product development, favoring an integrated environment in which individuals from different areas of knowledge contribute together to a valid product solution, justified by several criteria transversal to various areas. In product development it is unthinkable not to associate design, engineering and ergonomics. In fact, the market demands it and companies have to adapt themselves to these new demands: better products, better quality, better performance, lowest prices, and smaller delivery deadlines.

The application of this methodology in academic environment, particularly in product and industrial design courses, is a natural evolution that allows achieving a greater depth in detail, a more complete response in product development and, consequently, a greater preparation of their students to the new consumer requirements and business needs. As demonstrated by this case study, during the whole development process of the height-adjustable school chair, the cooperation between design and engineering was fundamental to the transformation of an idea into a commercial product. Still in the early stages, the relationship mechanism/form, engineering/design was evident in the evolution of the concept. It was even deeper and intrinsic in the dimensions definition, constructive solutions, and materials, where CAD software was an asset, and the exchange of concepts/knowledge among areas played a crucial role to achieve the final solution.

Based on the results of these three projects, it is possible to conclude that the integration of an interdisciplinary design methodology in the development of new products allows us to reach innovative and functional solutions, once creating a relation of sharing, both of knowledge and of methodologies, between design and engineering, there is a greater perception of the projects in question. By providing the designer with a greater number of information, his creativity is enhanced, thus solving the problems in an innovative and complete way. Combining this information with the use of creativity tools, in particular with the method of analogies, solutions to particular problems can be found in other ways.

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