Comfort driven design of innovative products: the case of the personalized mattress

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Abstract The application of ergonomic principles to the design of processes, workplaces and organizations is not only a way to respond to legal requirements but also an indispensable premise for any company seeking to pursue a business logic. The evolution of Human-centred design brings designers to focus their attention not only to the ergonomic performances of products and processes but, also, to the wellbeing of the customer/worker when interacts with the product. This wellbeing is often translated as the state of perceived (dis)comfort while performing an action. So, in recent years, methods that allow for an objective evaluation of perceived comfort, in terms of postural, physiological, cognitive and environmental comfort, have received a great deal of attention from researchers. The need to have an objective method to evaluate the (dis)comfort perception is definitively due to the will of introducing the comfort evaluation in the early stage of the product development plan, and the necessity to imagine and develop new methods for a preventive evaluation (often made on the digital model of the product) of the future perception of (dis)comfort of the customer. This works deal with the experience of designing an innovative product whose product-development-plan is centred on the customer perceived comfort: a personalized mattress. The mattress is the typical product whose relevance in everyday life of people is under-evaluated. People usually spend from 1/4 to 1/3 of their life on it, but nobody spends more than some minutes for choosing the right one when buying it. Fortunately, this trend is quickly changing and the customer pays more attention and takes information about producers and product characteristics before to buy a product. This trend is more evident in the market of high-performance (that means high price) mattress. Valflex is the luxury brand of Rinaldi Group S.r.l., one of the main player in the world of luxury mattresses' manufacturing companies. This company, together with University of Salerno, has developed methodologies both in terms of preventive comfort evaluation and in comfort-driven design. This work explains the results obtained through the profitable collaboration that allowed to develop two patents and a new reconfigurable mattress, easy to manufacture, whose layout can be tuned on the anthropometric data of the customer to improve the comfort experience during the sleep.

Keywords: Comfort, Mattress, Design

1 Introduction and state of the art

The application of ergonomic principles to the design of processes, workplaces and organizations is not only a way to respond to legal requirements but also an indispensable premise for any company seeking to pursue a business logic. The evolution of Human-centred design brings designers to focus their attention not only to the ergonomic performances of products and processes but, also, to the wellbeing of the customer/worker when

interact with the product. This wellbeing is often translated as the state of perceived (dis)comfort while performing an action. So, in recent years, methods that allow for an objective evaluation of perceived comfort, in terms of postural, physiological, cognitive and environmental comfort, have received a great deal of attention from researchers. The need to have an objective method to evaluate the (dis)comfort perception is definitively due to the will of introducing the comfort evaluation in the early stage of the product development plan, and the necessity to imagine and develop new comfort-driven method for designing new products whose main requirement is the wellbeing of the user. The mattress is one of these products and is the typical product whose relevance in everyday life of people is under-evaluated. One third of human lives are spent in sleep [1] and, in the majority of the world's modern and industrialized countries, this time is spent on a bed-system with a mattress. Sleeping time is very important for the human body to recover from both physical and physiological fatigue suffered throughout the day. Under an engineering point of view, the physical variables associated with sleeping comfort could include spinal alignment [2], contact pressure or weight distribution, interface skin temperature [3], and vapour exchange between the subject and the bedding system. Now, most of the studies and bedding system designs are focused on the measurement of human-back pressure to improve sleep quality and are presented mainly in the way of mattress firmness, but lack of exploring the real relationship between the sleeping postures and mattress design [4].
Going through a bibliographic research over the last 30 years, the first paper dealing with mattress design method is in 1993 [5] in which a pressure pad has been used for measuring the pressure at interface between users and hospital mattresses to develop guidelines for improving mattresses' performances. In recent years, two main approaches have been used to perform studies about the human-mattress interface behaviour; the experimental approach and the simulation approach. Using experimental approach, in 2008, Torres et al [6] have found the strong correlation among pressure variables (in particular pressure variance on buttocks and hands and pressure itself with entire body regions), perceived firmness and perceived comfort. Zhu et al. [7] demonstrated the positive influence of use of foams and latex in mattresses on perceived comfort. Bu et al. [8] demonstrated that the pressure generated through the use of different springs in the mattress frame (different elasticity) has a positive influence on the perceived comfort only in a specific range, thus the mattress needs to be not too firm and not too soft. Shen et al [9] demonstrated that the sleeping quality is correlated to the core material firmness in a three layered mattress (upper, core, bottom). Fang et al. [10] elaborated a simple method to weight the body parts through the pressure distribution on a pressure pad for improving the personalized comfort experience. In [11] Naddeo et al. demonstrated the effect of expectation in performing a mattress evaluation during buying time.
Using the simulation approach, in Ishihara et al [12] a FEM (Finite Element Model) model of soft body on a mattress has been used to evaluate the pressure at interface, with simulation error between 5% and 15%; in Lee et al. [13] a FEM approach has been used with very good correlation results. In Wu et al. [14] a rigid FEM manikin has been positively used to perform a correlation between mattress performances and pressure distribution; Scarfato et al. [15] worked for characterizing the foam mechanical behaviour for realizing really confident simulations.
The conclusion of mentioned papers drives the researcher to develop a method for designing new mattresses that have to be based mainly on the mechanical and the thermal optimization of the interaction between the human body and the mattress. Nevertheless, due to the comfort perception subjectivity, this is also depending from the variability of anthropometric characteristics of users; in Wong et al. [16] the need of customized mattress is highlighted.
In this paper, the problem of developing a new personalized mattress for optimizing the perceived comfort is studied and a practical solution, that have generated two patents, has been explained.

1.1 Aim of the study

The aim of this study was to develop a comfort-driven design method for bring innovation into a market in which it seems very difficult to do that: the mattresses' market.
The first target was to understand what can be the right way to change a standard mattress' configuration to achieve good results in terms of customers satisfaction and, in consequence, in terms of market share. The second target was to develop a new mattress that can be manufactured exactly as the old one, without introducing any kind of complication or new technology in the manufacturing process; the third target was to introduce

a real innovation, not only in the product, but also in the design process, through new methodologies and new instruments.
The case of a personalized mattress seemed to need a big effort and the authors, in cooperation with a mattress company, accepted the challenge.

2 Methods

The first question to which give an answer was: what does a mattress customer, want?
The answer seems obvious: he/she wants to sleep, to sleep well, to feel comfortable and to be refreshed after wake up! But the real behaviour of the customer is completely different: a customer that buy a mattress, in the majority of cases does not test the product or test it just for few seconds [3]; so, what can be done in order to give to customer the feeling of comfort during the first, quick, contact with the product?

Reasoning with these limitations in customer experience, we defined some target to be achieved:

1) The mattress has to be fit to use; in order to achieve this goal, each mattress has to fit to the customers' anthropometric characteristics: height and weight;
2) The sensation and the feeling the customer has during his/her first approach on the mattress, have to persuade him/her that the product fit perfectly with his/her needs.

The second question to which give answers was: what are the factors that influence a mattress' choice and which metric has to be used to measure them?
There are many objective parameters relating to subjective parameter of sleep (dis)comfort. Among various objective parameters, body pressure distribution, temperature and spinal alignment are considered as the critical factors with a substantial impact on sleep comfort and quality. Parameters within the pressure distribution closely correlated to sleep comfort are the maximum pressure, the average pressure [17], the maximum pressure gradient [18], the average pressure gradient, total pressure and total contact area [17] between human body and mattress. In addition, Shelton et al. [19] defined a Pressure Index called "Pindex" to evaluate the homogeneity of pressure distribution across the entire interface area.
On the basis of literature and of mattress company experience, the authors have chosen five parameters to describe the comfort perception, during a quick interaction, by the customer:

1) The average pressure at interface
2) The Variance of the pressure on the surface of mattress
3) The specific pressure distribution on shoulders, along the spine, on pelvis
4) The maximum pressure
5) The sinking into the mattress

The temperature was discarded because, in the buying moment, there is no enough time to reach the temperature equilibrium between mattress and customer laying on. The spinal alignment was discarded because the chosen posture (on the backs with head straight) for the test is the one in which poor sleepers spent more time [10, 15] and poorly affects the spinal alignment.
The analysis was based on a comparison with a reference mattress that was assessed [20] as an acceptable comfortable one, and can be considered as referral values for a used mattress.
All parameters described before were calculated using fully parametrized explicit FE (Finite Element) model that take into account the dynamic interaction between a manikin representing a human with its real joints, and a mattress.
The target of the company was to improve an existing mattress by a Knowledge Based approach for creating a fully configurable personalized mattress. The knowledge-based approach was integrated with the comfort driven analysis and a multiple solution synthesis.
We used a multi-expert system method [21] who recognized the critical factors, gave some guidelines for mattress improvement and evaluated the final solution. Solutions' space was gathered by a technological gate that gave us information about manufacturing feasibility and cost saving.

(1)

3 Comfort driven Innovation

3.1 The starting point

The starting point for new design development was an existing mattress that Rinaldi Group S.r.l. has in its own Commercial Catalogue: the Charlotte mattress, shown in Fig.1.

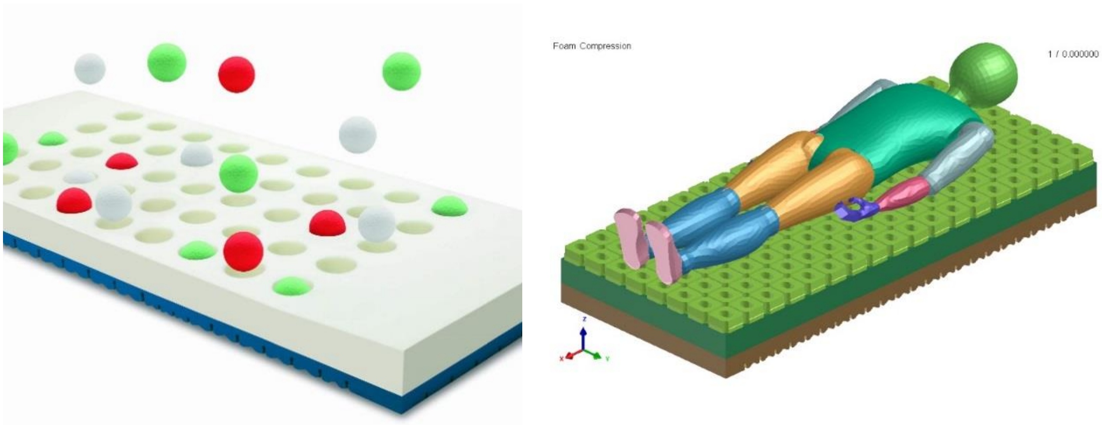

Fig. 1. The Charlotte mattress by Rinaldi Group (Internal part on the left, FEM model on the right).

As shown in the Fig.1, the Charlotte mattress is a three layers mattress made by three different foams: FF60N (High-density memory foam) for the upper part, AP35B (Low-density polyurethane foam) for the intermediate part and Viscopur (Viscoelastic high-density polyurethane foam) for the lower part. In the intermediate part, some balls made by AP35MS (Low-density polyurethane foam) are introduced in cylindrical holes to work as spring. This mattress was the starting point for innovation development.

3.2 Design Constraints

Authors and company engineers were subjected to several design constraints. The most important among them were the following:

1) Materials used for layers have to remain the same and in the same order (Top, Intermediate, Down). Only the content of the cylindrical holes can be changed;
2) The intermediate layer has to be manufactured in the same way (foam extrusion and cutting): the easiest way to respect this constraint is to not change the archetype of the mattress by changing at least the layout, the number and the dimension of the cylindrical holes;
3) The overall dimensions of the mattress have to remain the same due to the use of a textile envelope to wrap the foams layers. The company cannot change the envelope dimensions due to its costs;
4) The gluing systems and the glue type have to remain the same, in order to avoid new certification costs for new materials used in the manufacturing process;
5) New archetype of mattress needs to have the possibility to be personalized in an easy way, without incurring in technological problems or in troubles that might cause a delayed delivery to the customer.

3.2 Technology gate

Rinaldi Group S.r.l. imposed us some technology limitation in order to limit the costs of their innovation. Some technological issues are explained as follows:

1) Technologies used to manufacture the Charlotte mattress have to not be changed;
2) The new cutting systems has to be a cold mechanical cutting one in order to avoid chemical reactions or material's characteristics changes;
3) The mattress assembly operation needs to have the same processing time of the Charlotte one;
4) The assembly operation has to be performed by a robotized system;
5) The increase, in time, of manual operations have to be less than 20%.

On these bases, the new design has been thought.

3.2 The proposed solution

Due to design constraints and technology limitation, the real problem to solve was: what can be used to substitute the foam spheres and what kind of materials can be used to drive the comfort performances?
The basic idea was to fill the cylindrical hole with a special material in order to control the softness and the mechanical behaviour in compression. Material suppliers can offer to the company a wide range of foams from 25 to 65 Kg/m3 having two main behaviour in terms of hysteresis: Elastoplastic and memory foams. The choice was to fill completely the cylindrical hole by inserting a cylindrical-shaped piece of a specific foam among three kind of foams: a softer one, an intermediate one and a harder one. For each kind (soft, intermediate, hard) we had two choices of foam while we had the hypothetical possibility to change the holes diameters as we want. At the end, a unique cylindrical diameter was chosen (as a compromise between the available cutting systems and the workability of cut intermediate layer) and three foams (most performing in terms of durability and costs) were chosen. At this point, the great challenge was to choose the cylinders' layout. In the mattress, 45 cylinders have to be placed; the past knowledge about the mechanical behaviour of the mattresses allow to put some constraints, thus reducing the number of "free cylinders" from 45 to 12.
Due to the hypothesis of Symmetric behaviour of the mattress, the "free cylinders" were reduced to 6; thus, the potential layouts were 3^6 = 729 combinations.
Thanks to the expert consultancy and the previous knowledge about the foam behaviour and its influence on the comfort performances, we were able to drastically reduce the number of models on which perform the sleeping simulation to 15 models. Among 15, three were chosen as best fitting for 3 chosen application: sleeping comfort for a 50% Male with a weight of 60, 70 and 80Kg.

3.3 Technological analysis

The archetype choice allow us to immediately evaluate the changes needed in mattresses' process and the costs/time increase. An evaluation made by process experts bring us to an increase of about 7% of production time and a range of +5/10% in terms of costs.

3.4 Mattress and human modelling and characterization

All materials were physically tested by compression test following the ASTM standards [15] and materials' models were set in order to reach a numerical/experimental correlation of mechanical behaviour with an error always less than 5%, in terms of true-stress-true-strain curve and hysteresis/mechanical parameters.
The Cad model of the new mattress was created in ThinkDesign by Think3® Environment using a hybrid modelling approach (CGS – Constructive Solid Geometry and Surface Modelling). In order to create the model of

the human, we used a still developed MBS model in Solidworks that is fully parametrized in terms of anthropometric measures and human segments dimensions (length, volume, external surface shape) [22]. FEM models were created in VPS© (Virtual Performance Solutions) by ESI® (A dynamic explicit finite element solver) environment and prepared for the run.
Several hypotheses were made in order to simplify the calculations:

- The tests were made in supine position [10, 15] in order to perform a simple/symmetric analysis;
- The manikin was positioned and its joints were blocked in that position.
- All the manikin segments were treated as rigid body connected each other, in order to avoid to calculate flesh deformation during the interaction. This Hypothesis did not affected the calculation and the results because all mattresses were tested in the same conditions and also the referral mattress was tested in the same conditions.
- In order to simulate the body sinking in the mattress, a vertical velocity, from up to down, was imposed to the manikin. The mass distribution was set using the real human mass distribution into segments while the gravity force was neglected due to the use of a constant velocity.
- The equivalent mass of the manikin was calculated by integrating the calculated pressure at interface on the contact surface.
- The lower layer off the mattress was blocked on the ground by a 3DOF clamps (Z direction and rotations off plane)

Materials have been modelled by a nonlinear/viscous material for simulating the mechanical behaviour of foams. The calculation have been performed in order to have the following outputs:

- Map of pressures at interface between human body and mattress;
- Map of pressure at interface between the layers, in order to understand how much each layer works in terms of energy absorption and loads distribution;
- Z displacements of each node in contact with human body;
- Peaks of pressure.

3.5 Solution synthesis

In order to make a comparison between the previous mattress and the one with improvement/innovation, a comfort evaluation criterion was developed.
The comfort formula is protected by NDA (Non-Disclosure Agreement) but the mattress company Valflex permitted us to publish the qualitative information about it. The factors that have been taken into account are the following:

- Ratio between surface in contact with the human body and total surface, in order to take into account the "wrapping" effect;
- Average pressure on Human body that have been compared with the ideal one coming from literature [18,23,24];
- Maximum pressure, that is a good indicator of human body parts that can suffer local discomfort;
- Median Value and Variance of the pressure, that give an idea about the distribution and the difference between the body parts perception;
- Qualitative distribution of the pressure, evaluated by an expert;
- Values and distribution of the pressure in the shoulder/spine area, in order to take into account the discomfort in the body parts that are more sensitive when a person lie down on a mattress [25];
- Qualitative index about the load transfer between the layers, in order to evaluate how each mattress layer works.

All these parameters have been weighted in order to calculate a global comfort index for pressure/postural interaction with a formula like the following:

$$PC = \sum_{i=1}^{n} w_i \times Fc_i + \sum_{j=1}^{m} w_j \times Fs_j$$

In which PC = Perceived Comfort rating, w_i are the weights (relevance) of each evaluated parameter/factor, Fc_j are the n objective factors/parameters calculated by FEM analysis and Fs_j are the m subjective factors evaluated by the experts.
Fortunately, the experience of researchers and experts involved in the process and the limited number of possible layouts due to technological limitation allowed to use a “Trial&Error” method to perform the optimization steps.
The final product coming from this comfort-driven innovation process is shown in Fig.2:

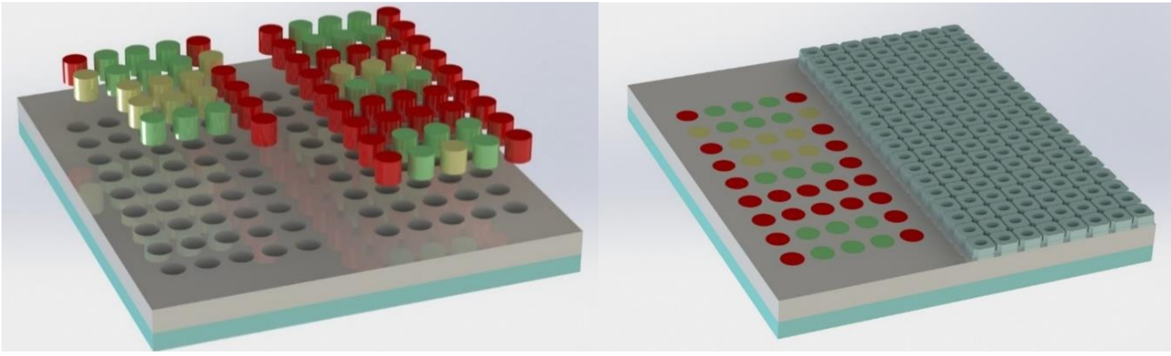

Fig. 2. The New Charlotte archetype.

4 Results

The final result of the innovation and optimization case is showed in Fig. 3-5:

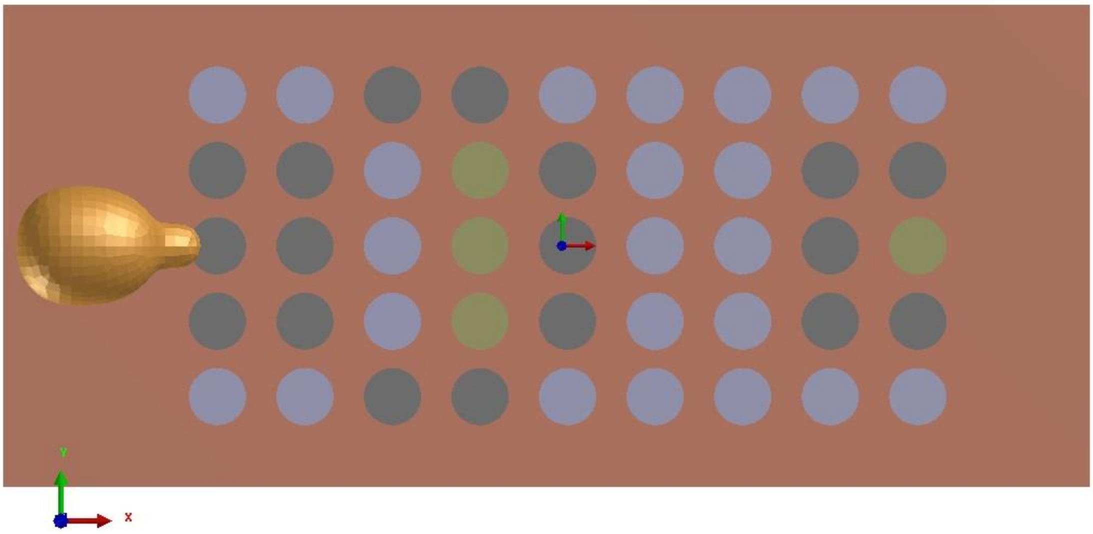

Fig. 3. Layout Charlotte for male 50%, weight 60 Kg

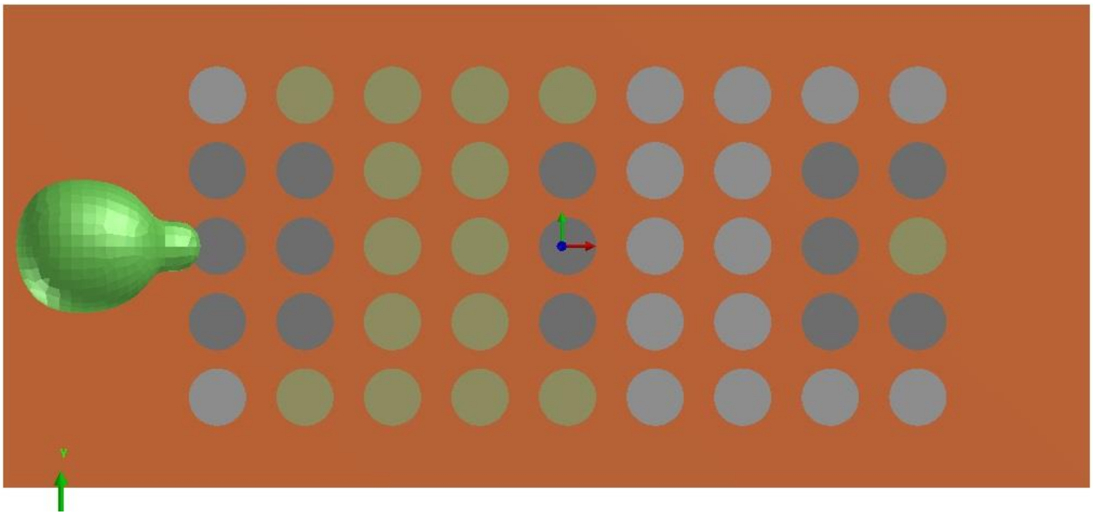

Fig. 4. Layout Charlotte for male 50%, weight 70 Kg

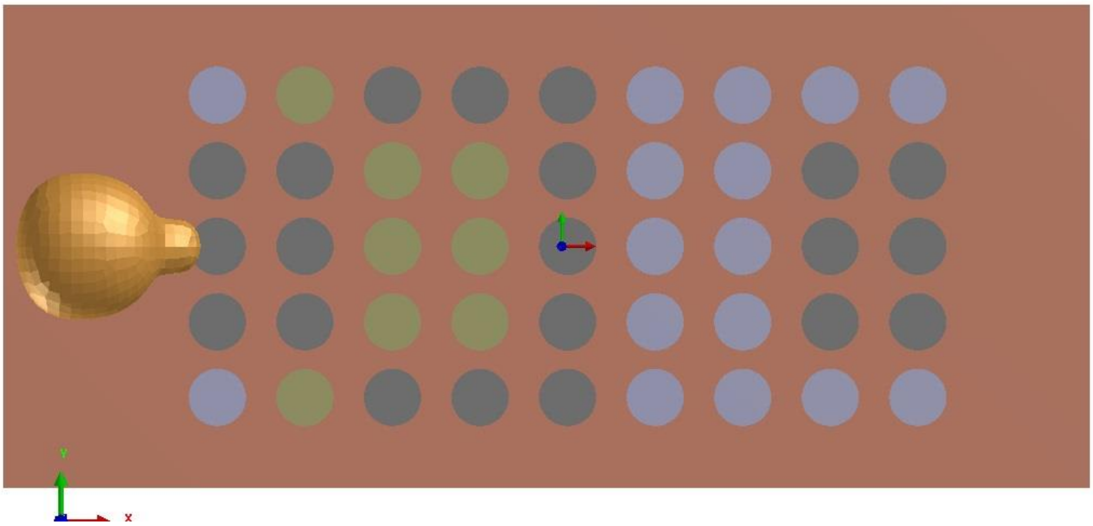

Fig. 5. Layout Charlotte for male 50%, weight 80 Kg

5 Conclusion

The mattress is a typical product whose relevance in everyday life of people is under-evaluated. People usually spend from 1/4 to 1/3 of their life on it, but nobody spend more than some minutes for choosing the right one when buying it. Since several years, the need of customized mattress is highlighted in both scientific literature and market advertisements.

In this paper, a methodological approach has been described to bring innovation by introducing a comfort-driven design method to improve an existing product without changing technologies and costs.

The study has been based on a simulation approach, with a partial correlation between numerical simulation and experiments (made on materials behaviour) that reached high level of precision (under 7% of error on the studied factors).

The new mattress is very easy to be assembled through the gluing of the different layers that constitute the mattress itself.

The comfort-driven design allowed to configure whatever different mattresses we want, and each of them is optimized for a pre-determined users belonging to an anthropometric cluster. The manufacturing cost of personalization is about near zero because the comfort optimization is done simply by adopting an appropriate layout of internal cylinders and using appropriate materials for them. The study was specialized for three different weights of a 50% European Male.
Through the easy personalization of the mattress, the new mattress can fit the customers' needs expressed not only in terms of preferences but also in terms of own anthropometric characteristics like height, weight (i.e. BMI). Therefore, the mattress company organized the new production process in cooperation with their foams' suppliers and had verified that the process times and costs remained almost the same.
Few experiments have been made on the physical prototype of the mattresses, giving very good results in term of perceived comfort. Next steps of this study will be an experimental assessment of the developed mattresses in order to scientifically prove the robustness of the design method.
Finally, this mattress has been introduced in the new Market Catalogue for 2018 and the Marketing&Strategy director of Rinaldi Group made a survey among their distributors and re-sellers and had a very interesting (good) feedback from the pilot customers.
Limitation of the study can be found in the FEM model used and in the wideness of the possible combinations that have been limited by several hypotheses and company's requests. Nevertheless, the study represents a good exercise of developing a comfort driven method with practical outputs.

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