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The 23rd CIRP conference on Life Cycle Engineering

Lifecycle optimization in the refrigeration industry: a Decision-Support Simulation Toolbox (DSST)

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Abstract

This paper presents a set of intermediate results related to the ELICiT project, whose purpose is the application of magnetic cooling technology within domestic refrigeration appliances. An innovative Simulation Toolbox, able to offer a better support to designers during the design process, was implemented. This way, a real time comparison of both economic and environmental variables related to magnetic cooling systems will be available. After the implementation phase, the Simulation Toolbox was directly tested in a real industrial context. Finally, gathered data were compared with conventional refrigeration solutions.

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1. Introduction

ELICiT ([www. http://elicit-project.eu/](http://elicit-project.eu/)) is a project funded by the European Commission concerning the development of an innovative magnetic cooling technology for the refrigeration sector. One of the objectives, besides the improvement and benchmarking of new technologies with the conventional ones, is the comparison and optimization of costs and environmental impacts generated along the whole lifecycle by alternative products. The aim of this paper is, therefore, to present an innovative Simulation Toolbox able to better support designers during the product development process, in order to consider both the two most important sustainability views (economic and environmental ones), with a direct comparison of performances.

The paper is structured as follows. Section 2 briefly presents the theoretical background behind the Simulation Toolbox, by introducing the Life Cycle Costing (LCC) and Life Cycle Assessment (LCA) methodologies. Section 3 describes in an extensive way the Simulation Toolbox conceptualization. Section 4 describes the Simulation Toolbox structure. Section 5 presents the industrial application of the Simulation Toolbox, by comparing the new gas-free magnetic

cooling technology with the conventional one. Section 6 discusses results coming from the previous application, by identifying strengths and weaknesses of the new technology in comparison to the conventional one. Finally, section 7 concludes the paper, by highlighting the next steps of the research.

2. Theoretical background

The focus of this section is to briefly show the theoretical background behind the Simulation Toolbox, by introducing the Life Cycle Costing (LCC), Life Cycle Assessment (LCA) and Life Cycle Optimization (LCO) methodologies. By assessing the scientific literature speaking about the application of these methodologies to the refrigeration sector it is possible to say that LCO is clearly focused on the optimization of two distinct areas:

- Performances, given a pre-defined set of target costs (e.g. investment and operational ones) and an overall environmental impact (e.g. in terms of CO₂ emissions or energy consumption);
- Costs and environmental impacts, given a pre-defined set of performances, features or components.

However, both the views seem to be poorly aligned with the sustainability assessment of products, but on the compliance with limits imposed by some business units within the company. From the LCA view, the literature showed a great focus on Beginning of Life (design and manufacturing of the product) and Middle of Life (use phase with related services). Finally, by considering LCC, the literature analysis highlighted a strong orientation on the assessment of costs accrued by customers (e.g. purchase and use energy costs) and manufacturers (e.g. raw materials / components and manufacturing energy costs). Instead, the End of Life point of view is partially considered by the experts during their calculations.

All these issues characterizing the reference literature clarified the need to support designers with new optimization tools with a better perspective on lifecycle costs and impacts related to alternative decisions that could rise during the development of new products.

3. Simulation Toolbox conceptualization

The Simulation Toolbox development follows a typical software development process. However, among all the software development phases, the most critical one is the requirements collection. In order to ease the gathering of information from ELICiT partners, an approach for software development has been implemented during the project. This approach wants to solve some particular issues affecting projects characterized by a high complexity and a high volatility in requirements definition. Figure 1 shows a dedicated model, where each cycle goes through four main phases: elicitation, analysis, specification and validation.

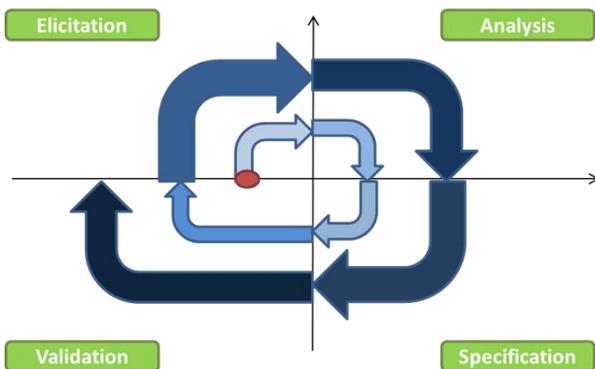


Figure 1: Requirements process model scheme

All these cycles are similar, except for the first one, having the role to initialize the process (introduction of the context and definition of the first draft of requirements). The other ones represent a continuous improvement of initial data. However, there are some factors affecting the overall number of cycles to be implemented, such as cost and time limitations. In fact, if limits (e.g. project milestones) are not respected, the process forces developers to move on to the next step. Unfortunately, this approach leads to a not consistent solution where requirements improve in detail but not in robustness. So, the probability and impact of future changes will increase. For this reason, a good practice consists

in delivering requirements as soon as possible to partners so to refine details during the implementation. Only this way there is a better communication and collaboration between partners and developers, by solving one of the main issues in software development, or the lack of knowledge about the final results to obtain.

3.1. Pre-elicitation

The pre-elicitation phase has been represented in Figure 1 as a red point. The purpose of this activity is to introduce the Simulation Toolbox idea to partners that, at the same time, expose their ideas and needs. To do that, it is of utmost importance to identify the context. Hence, it is necessary to gather some information related to partners in order to identify in advance any issue that has to be solved.

3.2. Elicitation

The aim of this phase is to gather designers' requirements and expectations. Designers' requirements describe both functional and non-functional elements without any technical description. They regard only specifications about the external behavior. Design and features will be provided later.

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In this phase the focus is to re-organize requirements in order to provide a whole view of the final project results. This has to be done to clean the whole amount of data from all the unnecessary information, evidence requirements with unclear (or missing) definitions and try to match the similar ones. At the end, a complete and robust list of requirements is available, so to avoid any sort of misunderstanding. Hence, it is necessary to make initial requirements more organized and synthesized in a well-structured tree, so to manage the individual requirements as they will emerge. By decomposing requirements into sub-requirements, the tree structure will be created automatically.

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The purpose of this phase is the explanation of functional requirements. In fact, the previous phases provided only the theoretical description. Now it is important to create the basis upon which to build the documentation. By doing so, specifications support developers in their evaluations during the next cycles. However, all the information needed regard only functional requirements. Non-functional requirements are not considered in this phase because they represent an intrinsic property of the system. Main purpose of this phase is to gather all the information for a proper understanding of designers' needs, in order to reduce the volatility due to changes and define a first draft of the final requirements that will be validated in the following step from the partner's point of view. Moreover, they represent the base from which developers will start to evaluate requirements feasibility.

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The purpose of the validation phase is to describe the list of final requirements to partners, in order to verify if current definitions fit their real needs.

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The first validation phase ends the initial cycle. From now, an iterative set of cycles, going ahead till the final implementation of the software, will start. A previous view of the software has been defined with partners and now it is necessary to increase their commitment, in order to define a clear and robust solution to implement. For each cycle, developers re-organize all the new requirements or changes coming from partners. The focus now is not only the gathering of information for the understanding of needs (and the reduction of the volatility of requirements due to partners changes), but also the management of volatility due to technological limits. The final validation phases assesses requirements from both partners and developers point of view. It represents the last review before the implementation of final requirements. After this last evaluation, requirements who reached a good level of specification and were approved by both partners and developers will be implemented.

4. Simulation Toolbox structure

A real application of what presented before is described in this section. In the ELICiT project case, pre-elicitation and elicitation were performed in a single stage. After a general comprehension of the refrigeration industry (allowed by a huge literature analysis – see Section 2), started a direct interview of technical partners. A questionnaire with a series of open questions was used for the gathering of needed data. This way, the ELICiT Simulation Toolbox development process started with the partner's requirements collection, according to the theoretical idea presented in the previous Section 3. Different partners reported needs, expectations and how these should be implemented into the final tool. The analysis phase was done gradually because from direct interviews emerged a sort of misalignment among requirements coming from different partners. So, the re-organization of initial requirements represented a great part of the work, and was done cyclically after each interview. Subsequently, functional requirements were discussed with partners, so to start in advance with the requirements feasibility assessment. The validation phase, together with additional iterative cycles, will be implemented in the next future, in parallel with the remaining ELICiT project activities. By considering the IDEF0 (Integration Definition) diagram reported in Figure 2, the Simulation Toolbox procedures applied and described up to now pertain to the first two blocks of the schematics.

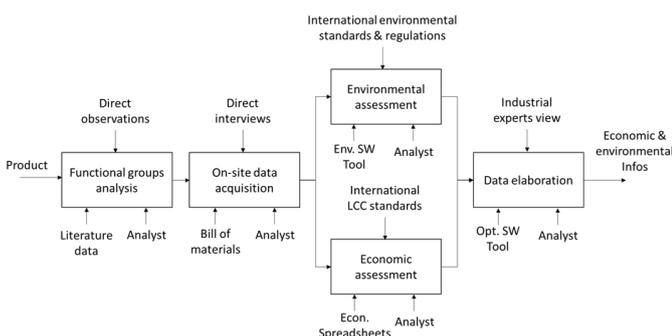


Figure 2: Simulation Toolbox contextualized IDEF0 schematics

Going into detail, the Simulation Toolbox logic follows different steps. The preliminary step (not reported in the IDEF0 diagram) allows to have a general description of the system taken into account, by defining a list of requirements selected for the final evaluation of results. The second step relates to the functional group analysis and the on-site data acquisition about available options, materials and weights of each component. The subsequent steps are differentiated between the environmental and economic contexts. In fact, input data are in common and collected at the beginning of the optimization process, directly from the field, but output are specific for each view. Finally, the data elaboration step matches environmental and economic data, by identifying the optimized solution.

In this case the contextualization of the Toolbox is related to the selection of software tools in support of the different methodologies constituting the overall optimization process. SimaPro® was selected as an ideal tool for the environmental assessment phase, because of the wide amount of libraries available and the easiness of customization. Microsoft Excel® will support the economic assessment because of its versatility to be hugely customized basing on different partners requirements in terms of costs to be controlled.

Physically, the ELICiT project wants to develop a Simulation Toolbox able to consider all the different existing phases along the product lifecycle, by considering both the manufacturing, use and disposal data. Such a Toolbox is needed by engineers and designers of modern companies, up to change their focus from a mere technical performance comparison to a more advanced sustainability performance comparison. More into detail, the Simulation Toolbox will be composed by two different types of tools:

1. An Economic Assessment Tool, in which the typical engineering simulations performed will be supported by economic indexes. In the project, an overall economic assessment tool has been developed, in order to give the possibility to designers and engineers to define how much their product configurations will cost during their whole life, before the real implementation. Within such a tool, the economic performance of the product along its life will be modeled, for example, from the point of view of materials and labor costs, commodities expenditures, etc.
2. An Environmental Assessment Tool, in which different resources consumption scenarios could be tested and compared in a virtual way. The different scenarios involving and interacting with the product along its life will be modeled and evaluated in terms of relevant performances (e.g. avoided CO₂ emissions, avoided waste of materials, etc.).

Furthermore, the Simulation Toolbox could be used at different levels of the design process (both for single components and whole products) and as cross-reference tool for the comparison of different domain solutions (both for

single components and whole products). Hence, it could be used to:

- Assess the viability of a current component (or sub-component) before its manufacturing;
- Assess the viability of a current whole product, given a pre-defined set of embedded components;
- Assess the viability of an innovative component (or sub-components), given a comparable current one;
- Assess the viability of an innovative whole product, given a comparable current one.

5. Simulation Toolbox industrial application

As already explained, the project domain is the refrigeration sector. Hence, the Simulation Toolbox has to be customized for the household refrigeration industry. This implies that the Toolbox has to cope with components and attributes of two different types of technologies: the current one (vapor compression) and the new one (magnetic cooling). This specific Toolbox will be a dynamic device for the magnetic cooling technology evaluation, which will be compared with the conventional vapor compression one, already well-defined and commercialized, both in specifications and standardized performances terms. The Toolbox will work into two levels of detail:

- At first level, the magnetic system and its components will be evaluated, by carrying out the best solution (or a list of solutions), and the best one will be defined through an Analytic Hierarchy Process (AHP) assessment;
- At second level, the results coming from the first level will be matched together (up to compose the virtual final product), and this last one will be compared with the conventional refrigeration system, giving designers an advanced decision-support tool.

The paper presents only the assessment of the first level, with the magnetic cooling machine evaluation.

It is important to notice that the evaluation will be not only restricted to the manufacturing phase, but to the entire lifecycle, so including the usage and disposal phases.

The first level of the Simulation assessment tool evaluates, simultaneously, different component alternatives, and their integration within the final product, by following the set-based principles. The set-based approach has been used for the evaluation, by analyzing technical and customer requirements. In fact, the Toolbox will take into account all the options which satisfy the established requirements. The set-based approach analyses all the combinations which respect concurrently the requirements. For this application two different types of requirements will be measured:

- Performance requirements;
- Customer requirements.

The set-based approach takes into account also the technical feasibility, which keep out combinations or options that are not possible in terms of feasibility. About this study, these are not taken into account because the selection of feasible set of components has been done in a previous phase, and cannot be recorded or assessed with an algorithm. For each component, options and requirements (both in performances or sustainability terms) have been identified, by following the process description reported in Section 3. At the end of this process, a matrix containing all the feasible combinations has been developed, and it has been used to implement the algorithm which will characterize the final spreadsheet. SimaPro® and Microsoft Excel® will use the

numerical contributions and pre-requisites gathered in this phase as input information for the environmental and economic assessment.

6. Results and discussion

As explained in several sections of the paper, the Toolbox will take into consideration LCA and LCC results for all alternatives throughout the whole lifecycle, to present the best solution, or the list of possibilities. The pre-definition of the analysis elaborate the goal and the scope for the Life Cycle Assessment, which will be used also for the economic analysis. The functional unit is one refrigerator during its life (10 years), excluding maintenance activities. The idea of the functional unit is to be representative with the system, and that can weight up different product typologies. The system boundaries considered for the evaluation is the entire lifecycle, from cradle to grave (from the environmental point of view only from cradle to the usage phase has been analyzed because of the uncertainty of the information related to the end of life). Figure XX shows the system boundaries included into the analysis. The figure represents all the information collected from the environmental point of view to describe the system. For each box an inventory of input and output has been collected.

Figure 3. System Boundaries

In particular, for each functional group elaborated during the Elicitation phase, a list of data about materials, processing and performances requirements has been done. Table 1 shows an example of data collection considering the cooling system and its components.

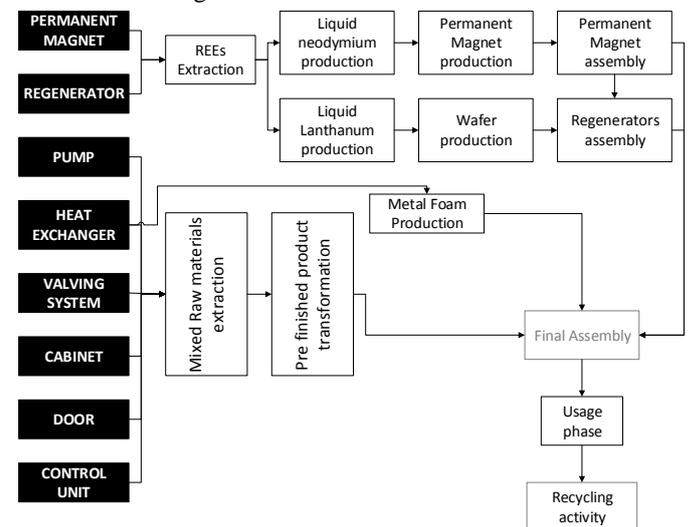
Table 1. Information required by the designers for product development. Starting point to identify the algorithm requirements.

Component	Type of info	Input required	Indicators
PUMP	Materials	Weight Extraction process	Procurement costs Env. Impacts
	Production process	Energy consumption Labor effort Scraps Pollutants	Estimated process costs Env. Impacts
	Technical performances	Overall efficiency Volume Lifetime Power range	Energy balance, spatial dimensions, reliability trend
HEAT EXCHANG ER	Materials	Weight Extraction process	Procurement costs Env. Impacts
	Production process	Energy consumption Labor effort Scraps Pollutants	Estimated process costs Env. Impacts
	Technical performances	Heat exchange rate Temperature drop	Warm vs cold side temp. Watts, COP index

Component	Type of info	Input required	Indicators
COOLING SYSTEM	Materials	Weight Extraction process	Procurement costs Env. Impacts
	Production process	Energy consumption Labor effort Scraps Pollutants	Estimated process costs Env. Impacts
	Technical performances	Overall efficiency Power range	Energy balance

Figure 4 and Figure 5 report the examples of the economic and environmental evaluation including all the required information. These figures are voluntarily reported in a small size in order to hide numerical values embedded into tables. These two Figures report the steps of lifecycle taken into account by the Toolbox, with their specific input and output.

The Simulation Toolbox presented within the paper has the main role of supporting the product design optimization process for each of the main components of a fridge. To this aim, the Toolbox was implemented as a unique instrument integrating all the aspects related to sustainability in a user-friendly workplace where designers and engineers could simultaneously manage both environmental and economic views, up to develop innovative products. At the end, three Simulation Toolboxes were simultaneously implemented, one for each main component of a magnetic refrigerator (or pump, heat exchangers, and cooling system, respectively). This way, results could be easily presented in the same context, both in numerical and graphical terms, and a direct comparison of several performance indexes will become immediate. From the environmental point of view, data represented a summary of results coming from an initial elaboration of information



given by several industrial experts through the SimaPro® software. From the economic view, the same elaboration of data was done directly through Microsoft Excel®. A sort of cockpit summarizes to users the results for both the two sustainability dimensions, by allowing them to modify any feature of components and directly assess the effect of their choices on the overall sustainability performance of the whole product (Figure 3 and Figure 4).

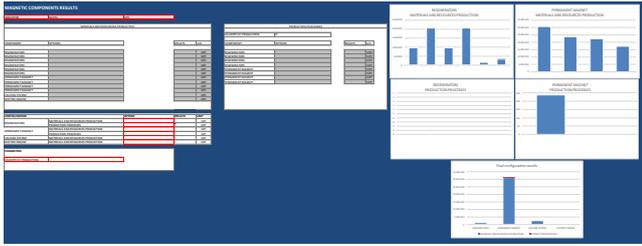


Figure 4. Environmental impact cockpit

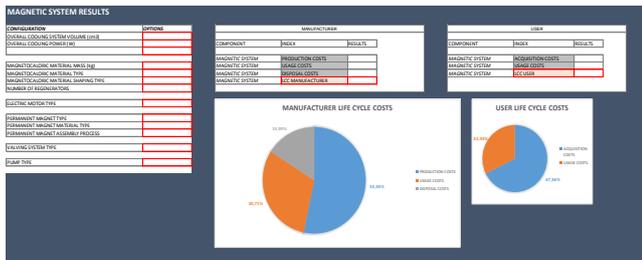


Figure 5. Economic impact cockpit

7. Conclusions

This paper described the first application of an innovative Simulation Toolbox at component level. As it can be seen from the work, different Toolboxes were developed for each of the main components constituting a magnetic refrigerator. However, the background logic is the same, following the LCA and LCC standards. This way, each actor can have a dedicated, and user-friendly, Simulation Toolbox supporting designers during the development of innovative components with a real time comparison of economic and environmental indexes and diagrams. During the assessment at system level, all the economic data related to different components coming from the various assessment tools will be summarized into a common workplace (a web-based one), allowing a better use from the household manufacturer's point of view.

Acknowledgements

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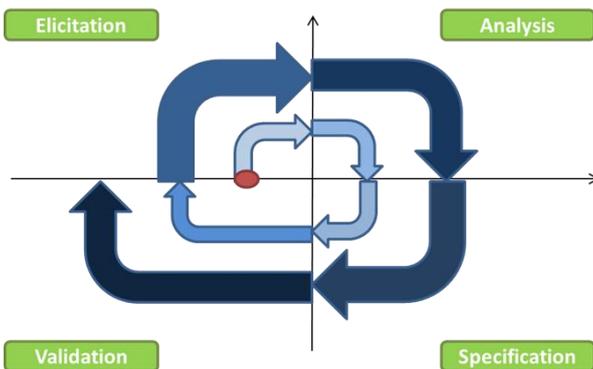


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A real application of what presented before is described in this section. In the ELICiT project case, pre-elicitation and elicitation were performed in a single stage. After a general comprehension of the refrigeration industry (allowed by a huge literature analysis – see Section 2), started a direct interview of technical partners. A questionnaire with a series of open questions was used for the gathering of needed data. This way, the ELICiT Simulation Toolbox development process started with the partner's requirements collection, according to the theoretical idea presented in the previous Section 3. Different partners reported needs, expectations and how these should be implemented into the final tool. The analysis phase was done gradually because from direct interviews emerged a sort of misalignment among requirements coming from different partners. So, the re-organization of initial requirements represented a great part of the work, and was done cyclically after each interview. Subsequently, functional requirements were discussed with partners, so to start in advance with the requirements feasibility assessment. The validation phase, together with additional iterative cycles, will be implemented in the next future, in parallel with the remaining ELICiT project activities. By considering the IDEF0 (Integration Definition) diagram reported in Figure 2, the Simulation Toolbox procedures applied and described up to now pertain to the first two blocks of the schematics.

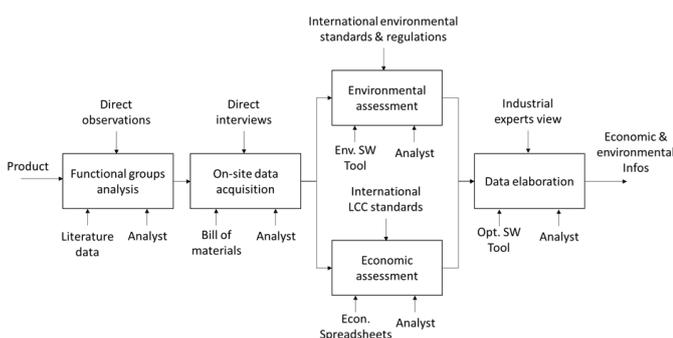


Figure 2: Simulation Toolbox contextualized IDEF0 schematics

Going into detail, the Simulation Toolbox logic follows different steps. The preliminary step (not reported in the IDEF0 diagram) allows to have a general description of the system taken into account, by defining a list of requirements selected for the final evaluation of results. The second step relates to the functional group analysis and the on-site data acquisition about available options, materials and weights of each component. The subsequent steps are differentiated between the environmental and economic contexts. In fact, input data are in common and collected at the beginning of the optimization process, directly from the field, but output are specific for each view. Finally, the data elaboration step matches environmental and economic data, by identifying the optimized solution.

In this case the contextualization of the Toolbox is related to the selection of software tools in support of the different methodologies constituting the overall optimization process. SimaPro® was selected as an ideal tool for the environmental assessment phase, because of the wide amount of libraries available and the easiness of customization. Microsoft Excel® will support the economic assessment because of its versatility to be hugely customized basing on different partners requirements in terms of costs to be controlled.

Physically, the ELICiT project wants to develop a Simulation Toolbox able to consider all the different existing phases along the product lifecycle, by considering both the manufacturing, use and disposal data. Such a Toolbox is needed by engineers and designers of modern companies, up to change their focus from a mere technical performance comparison to a more advanced sustainability performance comparison. More into detail, the Simulation Toolbox will be composed by two different types of tools:

1. An Economic Assessment Tool, in which the typical engineering simulations performed will be supported by economic indexes. In the project, an overall economic assessment tool has been developed, in order to give the possibility to designers and engineers to define how much their product configurations will cost during their whole life, before the real implementation. Within such a tool, the economic performance of the product along its life will be modeled, for example, from the point of view of materials and labor costs, commodities expenditures, etc.
2. An Environmental Assessment Tool, in which different resources consumption scenarios could be tested and compared in a virtual way. The different scenarios involving and interacting with the product along its life will be modeled and evaluated in terms of relevant performances (e.g. avoided CO₂ emissions, avoided waste of materials, etc.).

Furthermore, the Simulation Toolbox could be used at different levels of the design process (both for single components and whole products) and as cross-reference tool for the comparison of different domain solutions (both for single components and whole products). Hence, it could be used to:

- Assess the viability of a current component (or sub-component) before its manufacturing;
- Assess the viability of a current whole product, given a pre-defined set of embedded components;
- Assess the viability of an innovative component (or sub-components), given a comparable current one;
- Assess the viability of an innovative whole product, given a comparable current one.

5. Simulation Toolbox industrial application

As already explained, the project domain is the refrigeration sector. Hence, the Simulation Toolbox has to be customized for the household refrigeration industry. This implies that the Toolbox has to cope with components and attributes of two different types of technologies: the current one (vapor compression) and the new one (magnetic cooling). This specific Toolbox will be a dynamic device for the magnetic cooling technology evaluation, which will be compared with the conventional vapor compression one, already well-defined and commercialized, both in specifications and standardized performances terms. The Toolbox will work into two levels of detail:

- At first level, the magnetic system and its components will be evaluated, by carrying out the best solution (or a list of solutions), and the best one will be defined through an Analytic Hierarchy Process (AHP) assessment;
- At second level, the results coming from the first level will be matched together (up to compose the virtual final product), and this last one will be compared with the conventional refrigeration system, giving designers an advanced decision-support tool.

The paper presents only the assessment of the first level, with the magnetic cooling machine evaluation.

It is important to notice that the evaluation will be not only restricted to the manufacturing phase, but to the entire lifecycle, so including the usage and disposal phases.

The first level of the Simulation assessment tool evaluates, simultaneously, different component alternatives, and their integration within the final product, by following the set-based principles. The set-based approach has been used for the evaluation, by analyzing technical and customer requirements. In fact, the Toolbox will take into account all the options which satisfy the established requirements. The set-based approach analyses all the combinations which respect concurrently the requirements. For this application two different types of requirements will be measured:

- Performance requirements;
- Customer requirements.

The set-based approach takes into account also the technical feasibility, which keep out combinations or options that are not possible in terms of feasibility. About this study, these are not taken into account because the selection of feasible set of

components has been done in a previous phase, and cannot be recorded or assessed with an algorithm. For each component, options and requirements (both in performances or sustainability terms) have been identified, by following the process description reported in Section 3. At the end of this process, a matrix containing all the feasible combinations has been developed, and it has been used to implement the algorithm which will characterize the final spreadsheet. SimaPro® and Microsoft Excel® will use the numerical contributions and pre-requisites gathered in this phase as input information for the environmental and economic assessment.

6. Results and discussion

As explained in several sections of the paper, the Toolbox will take into consideration LCA and LCC results for all alternatives throughout the whole lifecycle, to present the best solution, or the list of possibilities. The pre-definition of the analysis elaborate the goal and the scope for the Life Cycle Assessment, which will be used also for the economic analysis. The functional unit is one refrigerator during its life (10 years), excluding maintenance activities. The idea of the functional unit is to be representative with the system, and that can weight up different product typologies. The system boundaries considered for the evaluation is the entire lifecycle, from cradle to grave (from the environmental point of view only from cradle to the usage phase has been analyzed because of the uncertainty of the information related to the end of life). Figure XX shows the system boundaries included into the analysis. The figure represents all the information collected from the environmental point of view to describe the system. For each box an inventory of input and output has been collected.

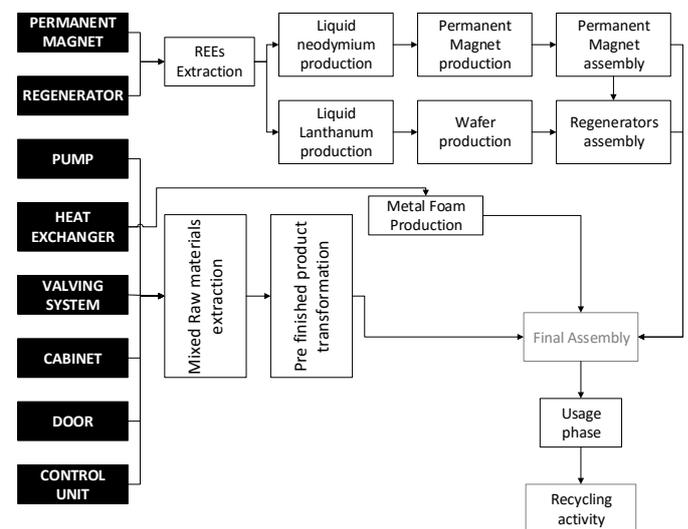


Figure 3. System Boundaries

In particular, for each functional group elaborated during the Elicitation phase, a list of data about materials, processing and performances requirements has been done. Table 1 shows an example of data collection considering the cooling system and its components.

Table 1. Information required by the designers for product development.
Starting point to identify the algorithm requirements.

Component	Type of info	Input required	Indicators
PUMP	Materials	Weight Extraction process	Procurement costs Env. Impacts
	Production process	Energy consumption Labor effort Scraps Pollutants	Estimated process costs Env. Impacts
	Technical performances	Overall efficiency Volume Lifetime Power range	Energy balance, spatial dimensions, reliability trend
HEAT EXCHAN GER	Materials	Weight Extraction process	Procurement costs Env. Impacts
	Production process	Energy consumption Labor effort Scraps Pollutants	Estimated process costs Env. Impacts
	Technical performances	Heat exchange rate Temperature drop	Warm vs cold side temp. Watts, COP index
COOLING SYSTEM	Materials	Weight Extraction process	Procurement costs Env. Impacts
	Production process	Energy consumption Labor effort Scraps Pollutants	Estimated process costs Env. Impacts
	Technical performances	Overall efficiency Power range	Energy balance

Figure 4 and Figure 5 report the examples of the economic and environmental evaluation including all the required information. These figures are voluntarily reported in a small size in order to hide numerical values embedded into tables. These two Figures report the steps of lifecycle taken into account by the Toolbox, with their specific input and output.

The Simulation Toolbox presented within the paper has the main role of supporting the product design optimization process for each of the main components of a fridge. To this aim, the Toolbox was implemented as a unique instrument integrating all the aspects related to sustainability in a user-friendly workplace where designers and engineers could simultaneously manage both environmental and economic views, up to develop innovative products. At the end, three Simulation Toolboxes were simultaneously implemented, one for each main component of a magnetic refrigerator (or pump, heat exchangers, and cooling system, respectively). This way, results could be easily presented in the same context, both in numerical and graphical terms, and a direct comparison of several performance indexes will become immediate. From the environmental point of view, data represented a summary of results coming from an initial elaboration of information given by several industrial experts through the SimaPro® software. From the economic view, the same elaboration of data was

done directly through Microsoft Excel®. A sort of cockpit summarizes to users the results for both the two sustainability dimensions, by allowing them to modify any feature of components and directly assess the effect of their choices on the overall sustainability performance of the whole product (Figure 3 and Figure 4).



Figure 4. Environmental impact cockpit

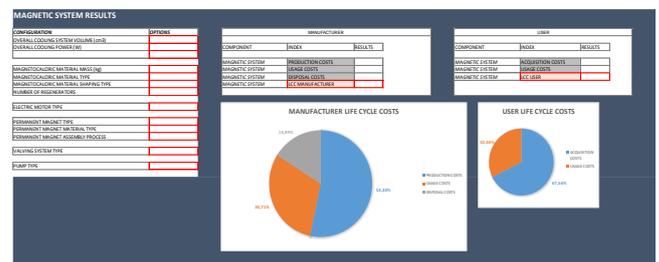


Figure 5. Economic impact cockpit

7. Conclusions

This paper described the first application of an innovative Simulation Toolbox at component level. As it can be seen from the work, different Toolboxes were developed for each of the main components constituting a magnetic refrigerator. However, the background logic is the same, following the LCA and LCC standards. This way, each actor can have a dedicated, and user-friendly, Simulation Toolbox supporting designers during the development of innovative components with a real time comparison of economic and environmental indexes and diagrams. During the assessment at system level, all the economic data related to different components coming from the various assessment tools will be summarized into a common workplace (a web-based one), allowing a better use from the household manufacturer's point of view.

Acknowledgements

This work was partly funded by the European Commission through the ELICiT Project (ENV-2013-603885, www.elicit-project.eu). In any case, the present work cannot be considered as an official position of the supporting organizations (EU Commission), but it reports just the point of view of the authors.

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Lifecycle optimization in the refrigeration industry: a Decision-Support Simulation Toolbox (DSST)

Dear Reviewers,

Thank you very much for your informed comments, which helped to improve this paper to the right standard considered for publication. We appreciated the time you spent in doing this. We tried to address all the issues you mentioned.

My colleagues and I have revised the paper basing on your valuable comments. I hope that now we will be able to reach the expected standard, worthy of publication in this journal.

A list of the answers to your precious suggestions is reported below.

Many thanks for your time and comments.

Reviewer #1: 1° comment

The topic is interesting, but the focus of the paper is wrong for LCE conference. The major part of the paper is quite standard description of a software project without any contribution to LCE research.

Response

Thanks for your kind comment.

Reviewer #1: 2° comment

Then the authors mention at the end, "From the environmental point of view, data represented a summary of results coming from an initial elaboration of information given by several industrial experts through the SimaPro® software. From the economic view, the same elaboration of data was done directly through Microsoft Excel®. A sort of cockpit summarizes to users the results for both the two sustainability dimensions, by allowing them to modify any feature of components and directly assess the effect of their choices on the overall sustainability performance of the whole product (Figure 3 and Figure 4)." It would be interesting to see what data was used and how they are summarized to evaluate the economic and environmental impacts.

Response

To better understand which data have been used, we added a figure defining "system boundaries", trying to explain all the lifecycle steps analysed. In addition, a table with information taken into account has been added at the end of the final section.

Reviewer #2: 1^o comment

Paper is well written and covers an important topic.

Response

Thanks for your kind comment.

Reviewer #2: 2^o comment

Figure 2 is not very legible and should be replaced.

Response

Done, thanks for your comment.