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Nfr-Based Framework For The Analysis Of Sustainability In Cyber-Physical Systems (Cps)

Marco basado en NFR para el análisis de la sostenibilidad en sistemas ciberfísicos (CPS)

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César Augusto Arce-Vargas
Universidad EAFIT - Universidad del Quindío. Medellín, (Colombia)
carceva@eafit.edu.co

Luisa Fernanda Restrepo-Gutiérrez
Universidad EAFIT. Medellín, (Colombia)
lrestrep18@eafit.edu.co

Elizabeth Suescún-Monsalve
Universidad EAFIT. Medellín, (Colombia)
esuescu1@eafit.edu.co

José Lisandro Aguilar-Castro
Universidad EAFIT. Medellín, (Colombia)
aguilarjos@gmail.com

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Abstract

The analysis of sustainability in Cyber-Physical Systems (CPS) and its connection to non-functional requirements (NFR) is crucial in today's context. The diverse range of contexts, concepts, design criteria, and perspectives among designers and researchers often leads to ambiguities and challenges in determining or measuring system sustainability. In response to this challenge, this article presents a proposed methodological tool with the primary aim of representing sustainability through the NFR Framework and elucidating the attributes contributing to its future operationalization. By identifying and analyzing non-functional requirements, the article suggests a series of inquiries to identify central aspects within the sustainability framework. Resolving these inquiries facilitates the assessment of these aspects on relevance scales defined according to the context. Designers and their teams can use this model to establish metrics that highlight the relationships and contribution levels of each non-functional requirement in support of sustainability. While the final weighting remains within the purview of the designer and team, the proposed model enables the documentation, standardization, and detailed definition of the undertaken process and the applied valuation scale.

Keywords
Sustainability; Cyber Physical Systems (CPS); SofGoal; Non-functional requirements (NFR); Metrics.

Resumen

El análisis de la sostenibilidad en los sistemas ciberfísicos (CPS) y su relación con los requisitos no funcionales se ha convertido en uno de los aspectos más críticos en la actualidad. La diversidad de contextos, conceptos, criterios de diseño y puntos de vista de los diseñadores e investigadores puede generar ambigüedades y dificultar la determinación o medición de la sostenibilidad de los sistemas. Para abordar esta problemática, este trabajo plantea una herramienta metodología cuyo principal objetivo es representar la sostenibilidad mediante el NFR Framework, y esclarecer los atributos que contribuyen para su futura operacionalización. A través del análisis y la enumeración de los requisitos no funcionales, se propone formular una serie de interrogantes que, al ser resueltos, permitan identificar aspectos primordiales en el marco de la sostenibilidad y evaluarlos en escalas de relevancia definidas de acuerdo al contexto. El diseñador y su equipo de trabajo podrían utilizar este modelo para establecer métricas que indiquen las relaciones y los niveles de contribución de cada uno de los requisitos no funcionales en favor de la sostenibilidad. Aunque la ponderación final recae nuevamente en el diseñador y su equipo, el modelo propuesto permite documentar, estandarizar y definir en forma detallada el proceso realizado y la escala de valoración aplicada.

Palabras Claves
Sostenibilidad; Sistemas Ciberfísicos (CPS); SofGoal; Requisitos No Funcionales (NFR); Métricas.

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I. INTRODUCTION

Cyber-physical systems (CPS), are technological structures that combine computational resources and physical devices in various processes in areas such as industry, agriculture, healthcare, and others, generating a significant social, ecological, and economic impact. In this context, the sustainability of CPS becomes a crucial challenge in a constantly evolving world. Sustainability has become a global priority, underscored by various initiatives emphasizing the importance of reducing energy consumption and carbon footprint. While these initiatives highlight Information and Communication Technologies (ICTs) as pivotal in achieving these aims, it's crucial to acknowledge that ICTs can also have adverse environmental effects. This article aims to elucidate the concept of software sustainability and its dimensions—human, environmental, and economic—alongside research endeavors in this domain [1].

Cyber-physical systems (CPS) encompass devices whose components facilitate interaction between machines and processes. A significant challenge faced by these systems today is their adaptability to changes during execution, given their implementation in environments of multidimensional complexity. Addressing this challenge involves integrating sustainability directly into the design of these systems. This article presents a systematic mapping study of the literature aimed at elucidating the current landscape of frameworks, designs, and/or models utilized during the initial stages of developing a cyber-physical system. The study reveals a lack of guidelines for constructing sustainable and adaptable cyber-physical systems. To tackle these challenges, a framework is proposed for analyzing, measuring, or determining the degree of sustainable CPS architectures. [2]. This method focuses on a set of metrics that enable the measurement of compliance with the system's non-functional objectives or requirements. The current work's proposal is initially developed by identifying a core set of NFRs (Non-Functional Requirements) from which potential additional NFRs are derived. Subsequently, a series of questions or inquiries are formulated to determine or evaluate the degree of compliance or operationalization. Following this, specific measures are defined to address these inquiries, ultimately facilitating an evaluation of the conformity or degree of compliance with the established metrics. The approach, which is based on GQM-O [2], is structured into four main levels:

Goal Level (G): This involves establishing metrics and relationships through objects or sets of specific references, identified via analysis from multiple perspectives within a previously defined environment.

Questions Level (Q): A set of questions is formulated to define or specify the characteristics the system must fulfill in terms of NFRs, focusing on a specific attribute or goal.

Metrics Level (M): Defining a set of metrics to evaluate each of the responses associated with different goals, using predefined scales set by the designer. Within this proposal, it is recommended to use weighting scales aligned with design premises or specifications.

Operationalization Level (O): Defining indicators and data collection procedures to assess the system's sustainability concerning established non-functional requirements. Procedures are established for gathering, analyzing, and interpreting results, facilitating an objective and systematic evaluation of attributes related to sustainability.

The concept of sustainability, from the perspective of non-functional requirements (NFRs), is crucial in understanding the contributions of the proposed SoftGoals. It encompasses the system's ability to maintain its functionality, reliability, and performance over time while adhering to environmental, social, and economic considerations. This perspective ensures that the SoftGoals not only address immediate operational needs but also contribute to the long-term viability and resilience of CPS in a sustainable manner.

This method focuses on defining one or multiple metrics that facilitate the measurement and evaluation of the system's objectives and non-functional requirements. The research proposal initially involves identifying a core set of NFRs, from which additional potential NFRs are derived. Subsequently, a series of targeted questions are formulated to assess the degree to which these NFRs are met or operationalized. Following this, specific measures are outlined to address these questions, thereby enabling an evaluation of compliance and the level of achievement for the established metrics.

The proposed SoftGoals are clear to individuals experienced in systems, which is a positive outcome. However, suggestions were received to refine the content for better understanding among those unfamiliar with this field. Ensuring accessibility and clarity for a wider audience is essential. Regarding potential adjustments or amendments, responses suggest that current changes are unnecessary. Participants believe that the existing proposal effectively addresses the project's scope. It is well-structured, thoroughly explained, and offers practical value for integrating sustainability attributes into the development of cyber-physical systems.

This positive feedback validates the robustness and significance of the presented proposal. Additionally, it emphasizes the perspective that new SoftGoals related to sustainability will likely be incorporated over time, aligning with the evolving nature of sustainability requirements in the realm of cyber-physical systems. The capacity to expand and adapt to emerging challenges and evaluation criteria is an essential attribute that ensures the proposal's continued relevance.

In summary, this article not only underscores the proposal's relevance but also provides constructive recommendations to enhance its comprehensibility. Furthermore, participants' feedback suggests that the proposed NFR-Based framework has the potential to emerge as a valuable tool for evaluating sustainability aspects in cyber-physical systems, as part of a comprehensive analysis that encompasses 20 related works, details the methodology employed, presents a validation model through focus groups, discusses the contributions of the study, and finally, offers conclusions based on the findings and results obtained. This outcome encourages further research and development in the field.

II. RELATED WORK

There are numerous studies focused on CPS with varied approaches to sustainability. Among those that have had a significant influence on the development of the proposal, the article titled "SinSO: Anontology of Sustainability in Software" [4]. This article addresses sustainability and its relationship with software quality attributes by establishing an ontology in the domain of sustainability. This ontology provides a fundamental tool for analyzing and identifying the relationships of quality attributes while offering terminology that supports the implementation of sustainable software projects. Its objective is to reduce inconsistencies and facilitate information exchange among designers and other stakeholders. SinSO covers the sustainable domain in its high-level aspects, establishing itself as a fundamental concept in terms of quality.

The article "Extending The NFR Framework with Measurable Non-Functional Requirements" [7] proposes a tool based on dependency graphs to bridge the gap between NFRs and their subsequent implementation. In this document, the concepts and graphical tools are used to represent the NFRs of the system under study. NFRs are represented as "softgoals," flexible goals that encompass qualities such as user-friendly, confidentiality, secure transactions, or easy maintenance. These flexible goals are denoted as softgoalssince they do not have a clear satisfaction criterion and often depend on the evaluator's perception. As stated in the article "Softgoals are satisfaced, ratherthansatisfied" [8], they are operationalized through the functionality of the system.

The article by MohdFahrul Hassan titled "A DecisionTool for Product Configuration Designs based on Sustainability Performance Evaluation" [9] proposes an analysis of sustainability in the product configuration process focused on performance sustainability. This study establishes seven stages or phases to consider using the Analytic Hierarchy Process (AHP). In the first phase, the main elements related to the system's sustainability and their corresponding metrics. Then, in the second phase, weights are assigned to each of them. In the third phase, the product to be evaluated is defined and subdivided into its basic components, different design alternatives are proposed based on morphological analysis, weighting is applied, and finally, a design is proposedbased on the basic components that meet the desired sustainability goals.

The methodological process reported by Capelli in Software Transparency [10] establishes a methodology for the analysis, weighting, and subsequent evaluation of software transparency as a non-functional requirement (NFR). It proposes the identification of core goals such as usability, auditability, and accessibility, among others. Then, derived goals linked to each of the main goals are identified, and they are substantiated based on their contribution to the main objective, in this case, transparency. The methodological model proposed by Capelliwas used as a guide to advance towards a more efficient and responsible implementation of non-functional requirements with a focus on sustainability in CPS.

The book by Chung [8] on non-functional requirements (NFRs) proposes a list of NFRs to be considered in the design and subsequent analysis of systems. One of the key concepts is that of "Softgoals" or Flexible Goals that should be achieved and help represent the objectives while evaluating their degree of fulfillment. The model provides a structure to represent and store design and reasoning processes in graphs called "softgoal interdependency graphs (SIGs)." These graphs capture design considerations and their interdependencies and, through the use of labels, establish the degree of goal fulfillment.

Lastly, as a guiding document, "A sustainable development approach for self-adaptive cyber–physical systems life cycle: A systematic mapping study" [11] identifies dimensions related to sustainability and their different relationships. This document describes a systematic mapping model aimed at analyzing different methodologies in the development of self-adaptive CPS with a focus on sustainability. It presents a general description of the strategies used for the development of Self-Adaptive CPS (SA-CPS), the gaps found in each stage of the System Development Life Cycle (SDLC), and the focus given to specification analysis, considering aspects such as: Who will use the system? What should the system do? and where will it be used? These aspects are considered vital when approaching sustainability in CPS."

In summary, these documents have enriched the current proposal by providing concepts and approaches that contribute to the aspects of sustainability in cyber-physical systems. However, none of them establish a methodological model to measure or determine the fulfillment of Non-Functional Requirements (NFRs). The article "SinSO: An ontology of Sustainability in Software" introduces an ontology in the domain of sustainability in software, which is essential for analyzing and identifying the relationships between quality attributes and supporting the implementation of sustainable software projects.

III. METHODOLOGY

The proposed methodology is based on the use of Graphic Interaction Systems (SIG) model to represent, analize and evaluate the sustainability of cyber-physical systems (CPS) from aspects called flexible goals or 'softgoals.' The main objective of this methodology is to provide a clear and structured analysis that allows determining the sustainability levels of a CPS and understanding how different attributes contribute to that sustainability. To establish metrics for the different contributions, sign representation is employed, where positive satisfaction is represented by the sign (+), strong positive satisfaction is represented by (++). On the other hand, negative contribution is represented by the sign (-), and strong negative contribution by (--). Based on the identified and represented NFRs (Non-Functional Requirements) in the ontology [6], the foundations are established for the proposal and the final SIG focused on sustainability.

Firstly, five main attributes or central softgoals were established, namely: Reliable, Secure, Economical, Ecological, and Social, which directly contribute to sustainability. These attributes were established based on the ontology proposed in SINSO[4], which provides clear terminology and a reliable foundation for the development of software with a focus on sustainability (See Fig 1).

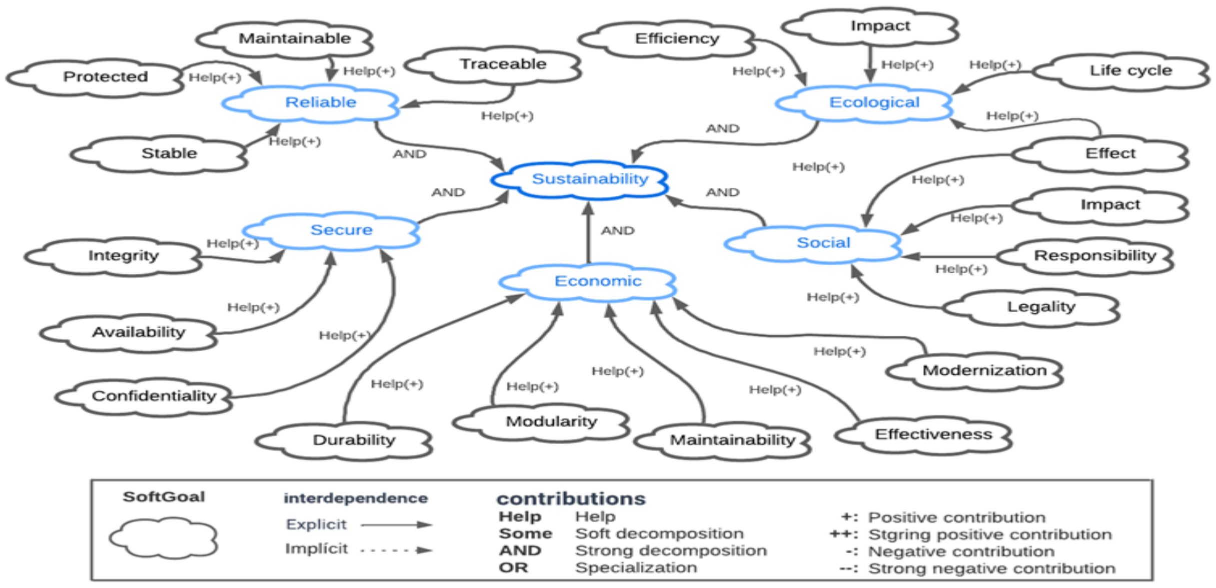


Fig 1. Sustainability SoftGoals. Source: self-made

Once the SoftGoals have been established, the SIGs model is used for their representation and the corresponding relationships. The model consists of nodes and links. Nodes represent the objectives that need to be fulfilled in a specific context, while links determine the positive or negative contributions between them. The model allows for different types of contributions, such as strong decomposition (AND), specialization (OR), soft decomposition (some), and goal help (Help). To establish metrics and evaluate the contributions, signs are used to represent positive contribution (+), strong positive contribution (++), negative contribution (-), and strong negative contribution (--). These metrics allow determining the degree of fulfillment of each attribute and its contribution to the overall sustainability of the CPS [8].

The proposed methodology places a strong emphasis on contextualizing definitions for each of the objectives outlined [6], [7], [8], [11]; It is important to note that the definitions were contextualized with a focus on the sustainability of cyber-physical systems (CPS). It is worth clarifying that while the analysis primarily focuses on the software domain, some non-functional requirements (NFRs) are focused on the physical component as it was considered relevant to the object of study. The definitions of the Soft Goals related to sustainability and the reference frameworks of the NFRs are detailed below:

- Reliable: This refers to the system's ability to maintain its intended behavior even in the face of component failures or deviations from normal operating conditions[8].

- Secure: This focuses on the system's ability to withstand external attacks and prevent unauthorized alteration or disclosure of data [8].

-Economical: This aspect refers to the economic impact, particularly in terms of reducing production times, increasing productivity, saving energy, and meeting specified requirements [8].

- Ecological: Focused on the impact (positive or negative) that the system has on the environment and the ecosystems it interacts with. This includes aspects such as the management of renewable resources and clean energy [8].

- Social: This aspect emphasizes the system's impact on human activities and the social groups directly involved. It encompasses considerations related to social welfare, equity, inclusivity, and the promotion of positive social interactions [8].

From here, questions should be posed to be evaluated by the designer of the CPS in order to assess the degree of fulfillment or satisfaction of the system's sustainability, in accordance with each of the previously established SoftGoals. Subsequently, a validation scale should be established based on the relationship between sustainability goals and the system's main objective. The designer will establish the priority or significance of NFRs, considering their importance within the system's context; For example, if the primary goal of the CPS is environmental sustainability, prioritizing it over secondary aspects like economic sustainability, greater weighted importance will be given to the fulfillment of ecological goals.

Now, let's analyze each of the central SoftGoals and their corresponding derived SoftGoals. In each case, we will provide examples of possible questions that the designer could consider when analyzing the CPS under study, in order to determine, to some extent, the sustainability of the system:

Reliable

As a first step, we analyze Reliability and its related or positively contributing goals. Reliability in a system is affected by a series of threats called faults, errors, and failures [12]. Failure is an event that occurs when the delivered service deviates from the expected or correct service [14]; An error is a part of the system state that can cause a service failure, and a fault is defined as the hypothetical cause of an error [12]. An error is also defined as the total part of the system state that leads to subsequent service failures. The various ways in which a system can fail to provide a service are referred to as failure modes [13]. Users expect their devices to function continuously and according to the specifications for which they were designed. For example, a vehicle user expects it to perform according to their expectations of operation, fuel consumption, and safety for its occupants. In the case of CPS, these expectations are increased because, as mentioned before, they are used in critical applications. On the other hand, CPS face unpredictable environments and operate in environments that should be highly controlled. However, they must have strong resilience to unexpected conditions while simultaneously adapting to errors in their components or subsystems.

The challenge lies in obtaining the best configuration and interrelation of a carefully selected series of components on a specific hardware platform. In general, CPS focus on monitoring and feedback processes of variables involved in the subsystems and their influence on the final outcome of the process.

Numerous applications are associated with critical activities, where external interferences or security breaches can lead to catastrophic consequences. Therefore, reliability is one of the most important aspects to consider. This is why we propose analyzing the SoftGoal (Reliable) through four implicit goals that have a positive contribution or help the higher-level goal: Traceable, Maintainable, Protected, and Stable (See Fig 2).

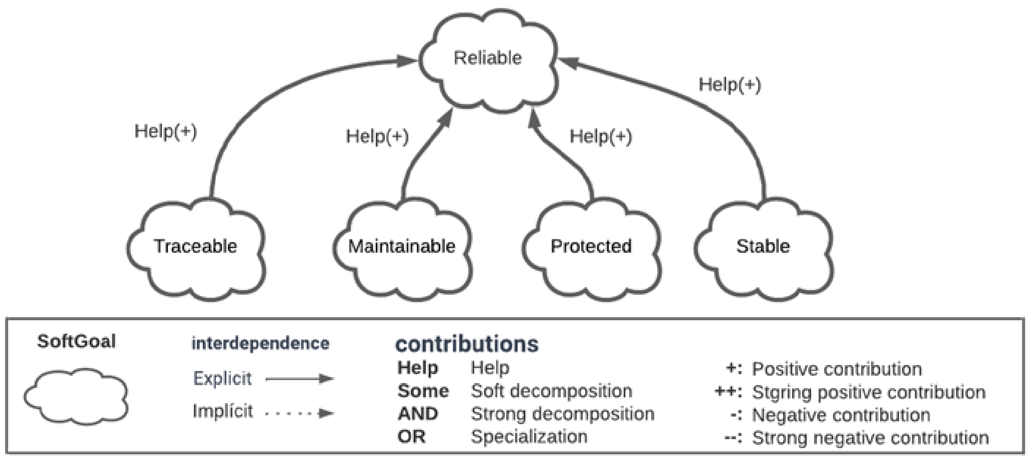


Fig 2. SoftGoal - Reliable. Source: self-made

Following the established procedure, we propose the subsequent definitions contextualized to CPS, along with our approach for the related second-level soft goals:

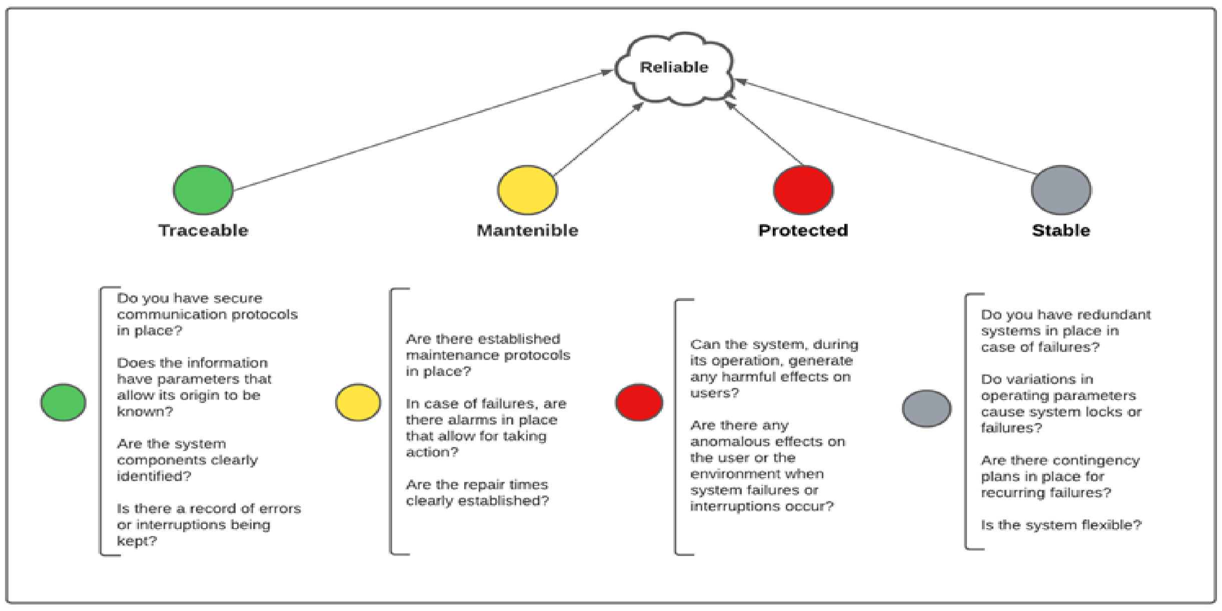
- Traceable: The system's ability to identify the origin of data, and overall information related to its operability[8].

.- Maintainable: The system's ability to be fully repair at an operational level within established time parameters. It should have monitoring tools that allow complete tracking of the system's operations within a timeframe in line with the established design procedures[8].

- Protected: The system's ability to operate without generating consequences for the user or the environment[8].

- Stable: The system's ability to operate even in the presence of component failures. The system has options or alternatives to ensure its operability[8].

Once the SoftGoals and their relationships with the higher-level goal have been identified, specific questions are posed to elucidate the objectives in a more specific manner and establish metrics that allow for determining levels or degrees of goal fulfillment. Fig 3 illustrates an example of questions related to the Reliable SoftGoal that lead to operationalization:



Do you have secure communication protocols in place?

Does the information have parameters that allow its origin to be known?

Are the system components clearly identified?

Is there a record of errors or interruptions being kept?

Are there established maintenance protocols in place?

In case of failures, are there alarms in place that allow for taking action?

Are the repair times clearly established?

Can the system, during its operation, generate any harmful effects on users?

Are there any anomalous effects on the user or the environment when system failures or interruptions occur?

Do you have redundant systems in place in case of failures?

Do variations in operating parameters cause system locks or failures?

Are there contingency plans in place for recurring failures?

Is the system flexible?

Fig 3. Catalog - Reliable. Source: self-made

The evaluation of the questions and their subsequent prioritization or relevance levels depends on the scope of the application and the central objectives. For instance, when evaluating stability in the face of failures, questions like “Are redundant systems in place in case of failures?” are raised. The fulfillment of this characteristic will depend on the level of operational availability of the system. In other words, if the application is a critical system (a system that must function continuously), such as a life support equipment in an intensive care unit or a traffic control system, this parameter will have a priority consideration and its fulfillment will be mandatory. On the other hand, in another application context where system failures can occur within specific time periods, it could be that this attribute is not fundamental or mandatory.

Secure

The intrinsic relationship between hardware and software results in classical security concepts such as confidentiality, integrity, and availability taking on renewed validity in the specifications of CPS [4]. It is necessary to analyze the impact of external attacks or interferences on the system and their effects on its functioning and the potential consequences for critical processes it performs, considering the non-homogeneity of the functions performed by the involved components. The increasing connectivity of CPS has introduced new challenges related to security, especially when systems use public networks like the Internet for transmitting parameters and information, making them susceptible to possible cyberattacks [14]. CPS networks are commonly composed of a series of elements that interact with each other in complex and changing ways. These systems combine a variety of components, such as programmable logic controllers (PLCs), sensors, actuators, network devices, and industrial communication protocols. Their objective, in many cases, is to perform daily tasks of vital importance and with a significant impact on production processes [15]. To analyze the security characteristics of the system, three flexible goals are proposed to characterize the system, which help or contribute to the main goal (Fig 4): Integrity, Availability, and Confidentiality.

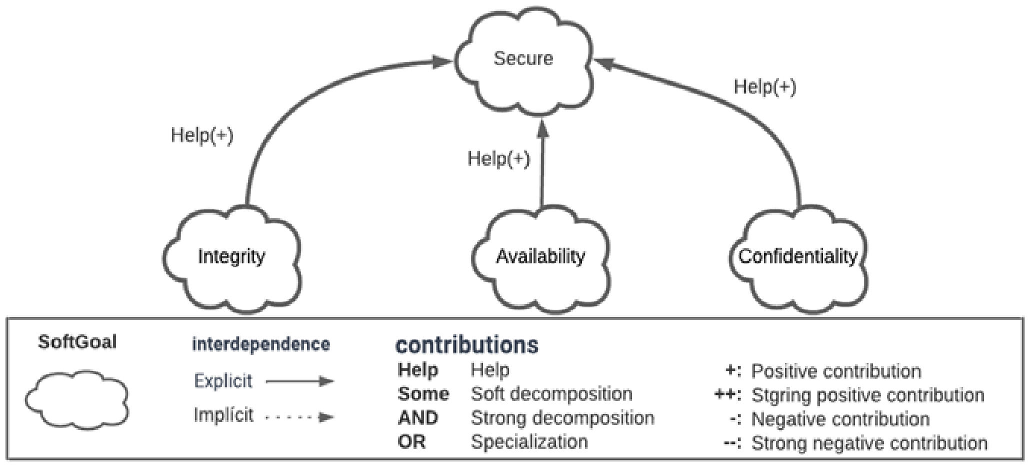
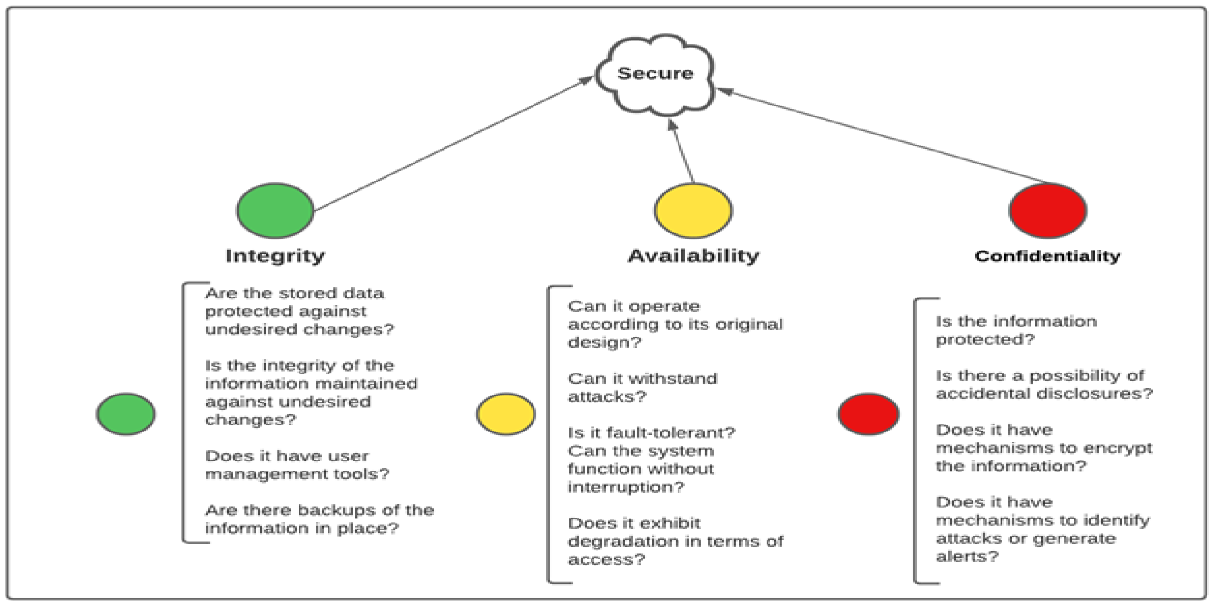


Fig 4. SoftGoal - Secure. Source: self-made

Having specified definitions for each of the related second-level softgoals, the following definitions are proposed:

- Integrity: The system's ability to ensure that information is not altered by external means, manage users, system components, and their roles. Users refer to both people and system components that require services[8].
- Availability: The system's ability to continue operating properly even in the presence of unwanted external attacks or disturbances. The system should continue functioning without degradation in terms of access and be capable of providing resources required by authorized users when they need them (ensuring accessibility to authorized elements)[8].
- Confidentiality: The system's ability to guarantee the protection of information and safeguards against unintended disclosures. The system should have access control mechanisms that ensure the confidentiality of information[8].

Similar to Reliability and in accordance with the proposed GQM methodology, questions focusing on system security need to be established to assess the degree of compliance based on the system's expected characteristics. Fig 5 illustrates an example of questions related to the Reliable SoftGoal that lead to operationalization.



Are the stored data protected against undesired changes?

Is the integrity of the information maintained against undesired changes?

Does it have user management tools?

Are there backups of the information in place?

Can it operate according to its original design?

Can it withstand attacks?

Is it fault-tolerant? Can the system function without interruption?

Does it exhibit degradation in terms of access?

Is the information protected?

Is there a possibility of accidental disclosures?

Does it have mechanisms to encrypt the information?

Does it have mechanisms to identify attacks or generate alerts?

Fig 5. Catalog - Secure. Source: self-made

Ecological

To address the sustainability of CPS with a focus on ecological impact, it is worth noting the global concern for integrating ecological and economic variables, giving rise to concepts such as eco-development, integrated development, organic growth, and various interpretations of the term "sustainable development.". "Sustainable development is the development that meets the needs of the present generation without compromising the ability of future generations to meet their own needs" [16]. In [17] states that "a sustainable society is one in which resources are not used at a rate faster than they can be regenerated, pollutants are not emitted at a rate faster than the natural system can absorb, and non-renewable resources are used at a rate slower than human-created capital can replace lost natural capital". With this premise in mind, CPS have an unavoidable commitment to sustainability and should strive for sustainable development.

The concept of the 6Rs (Reduce, Reuse, Recycle, Recover, Redesign, and Remanufacture), as analyzed by Jawahir IS [18], presents a series of elements that can be applied to the analysis of sustainability in the implementation and use of CPS. This analysis considers the impact of implementation, as well as the impact generated by their use and final disposal. "An axe can be made from recycled steel but be used to clear-cut a forest" [19]. To evaluate the sustainability of CPS with a focus on ecological impact, the following SoftGoals are considered (Fig 6).

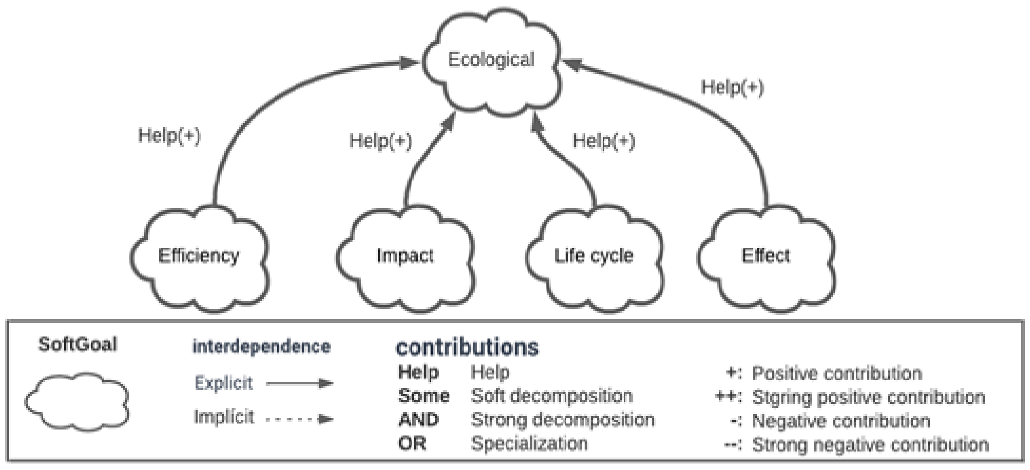
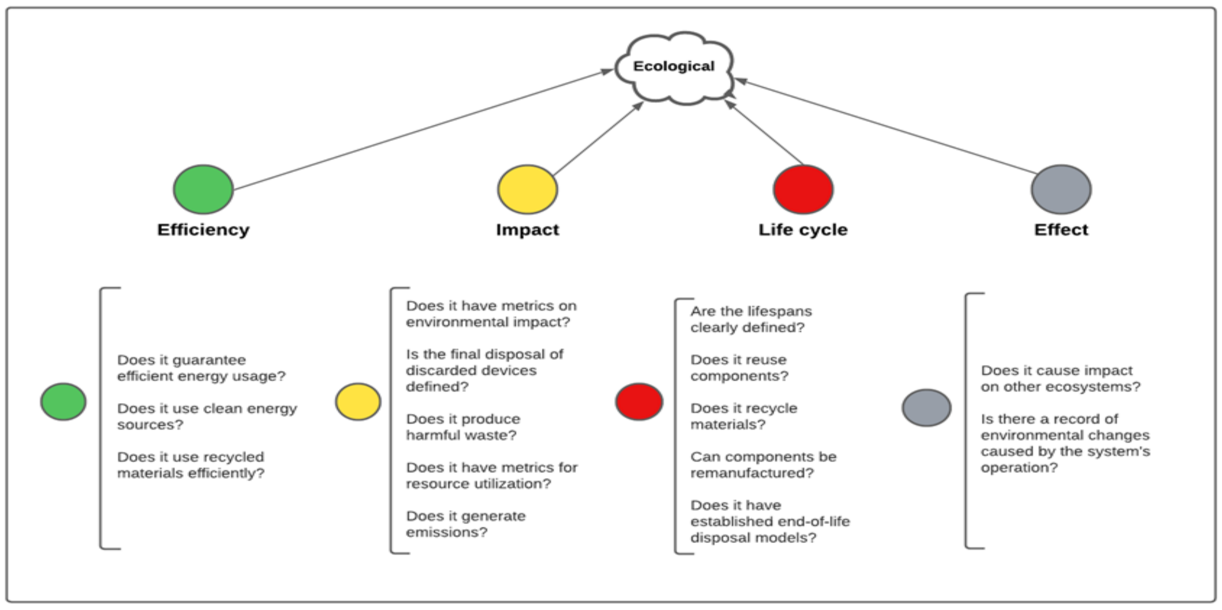


Fig 6. SoftGoal - Ecological. Source: self-made

For each of the SoftGoals related to Ecological, which are directly related to the physical aspect of CPS, we have:

- Efficiency: This includes aspects related to the balance between ecological impact and the efficient resource utilization[8].
- Impact: Specifications related to the direct impact on the environment and resulting footprints from the use of the system[8].
- Life cycle: Focuses on evaluating aspects related to recycling, waste disposal, component remanufacturing, reuse, and disassembly. It considers the regional and global impact of the system throughout its life cycle and promotes clean and eco-sustainable processes[8].
- Effect: Considers the use of renewable materials and resources, as well as the overall balance between system operation and the generated impact[8].

In accordance with the proposed GQM methodology [8], Fig 7 illustrates the suggested questions with an ecological focus.



Does it guarantee efficient energy usage?
Does it use clean energy sources?
Does it use recycled materials efficiently?

Does it have metrics on environmental impact?
Is the final disposal of discarded devices defined?
Does it produce harmful waste?
Does it have metrics for resource utilization?
Does it generate emissions?

Are the lifespans clearly defined?
Does it reuse components?
Does it recycle materials?
Can components be remanufactured?
Does it have established end-of-life disposal models?

Does it cause impact on other ecosystems?
Is there a record of environmental changes caused by the system's operation?

Fig 7. Catalog - Ecologic. Source: self-made

Economic

We will focus on verifying the fulfillment of economic objectives that promote appropriate progress, productivity, competitiveness, and economic growth, all within an efficient framework of wealth accumulation and equitable distribution. To achieve this, we will focus on improving production times, profitability, energy efficiency, the use of renewable resources, on-demand manufacturing, and waste reduction (Fig 8).

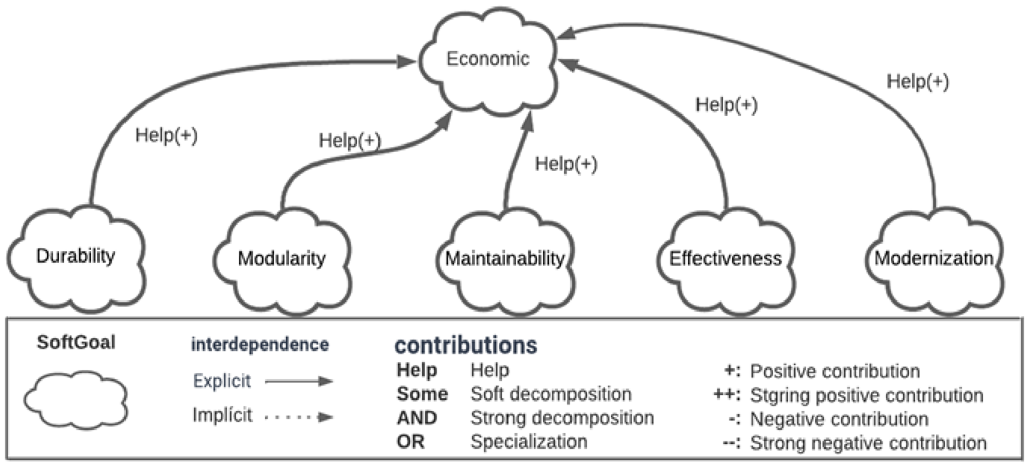


Fig 8. SoftGoal - Economic. Source: self-made

Continuing with the established procedure, the following definitions are proposed, contextualized to CPS and our approach for the related second-level softgoals:

- Durability: Related to the operational lifespan of the system directly associated with return on investment and profitability[8].

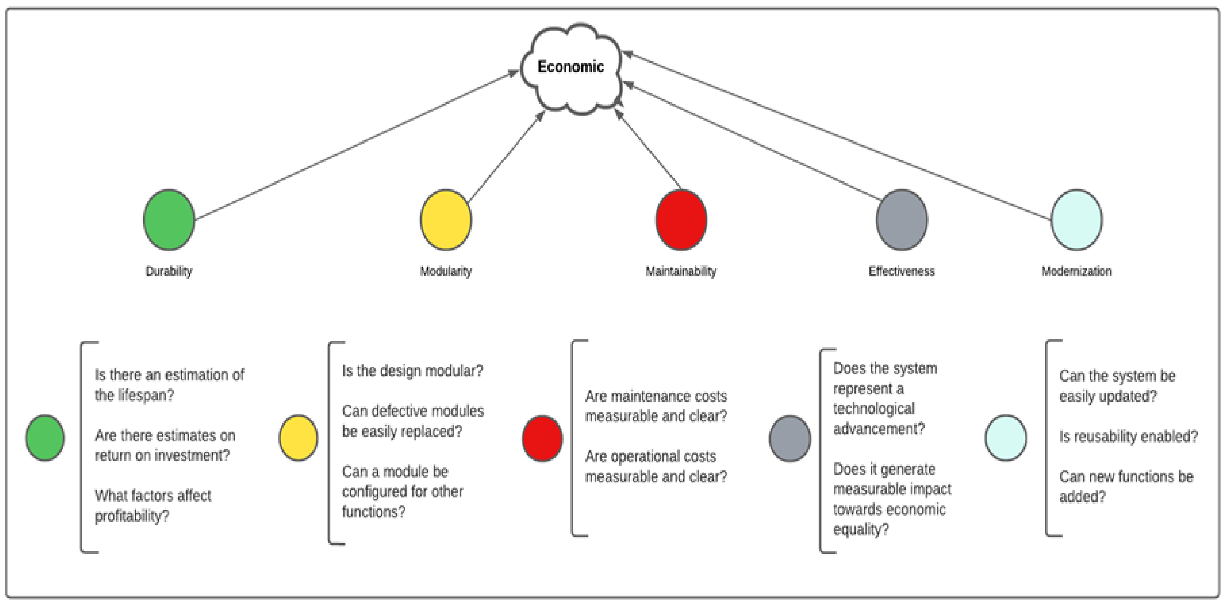
- Modularity: The property that allows a system to be divided into smaller parts (modules), each of which is as independent as possible, facilitating replacement without affecting the overall system[8].

- Maintainability: From a physical standpoint, it relates to the costs of maintenance and operation of the system (operational efficiency). From a software perspective, it relates to the system's capacity for evolution[8].

- Effectiveness: An indicator of the technological advancement generated by the system and the opportunities for new applications. It has an impact on promoting economic equity[8].

- Modernization: An indicator of the system's ability to be updated using the same components (reuse) without altering its overall structure[8].

Fig 9 provides some suggested Questions for analysis with a focus on the Economic goal.



Is there an estimation of the lifespan?

Are there estimates on return on investment?

What factors affect profitability?

Is the design modular?

Can defective modules be easily replaced?

Can a module be configured for other functions?

Are maintenance costs measurable and clear?

Are operational costs measurable and clear?

Does the system represent a technological advancement?

Does it generate measurable impact towards economic equality?

Can the system be easily updated?

Is reusability enabled?

Can new functions be added?

Fig 9. Catalog - Economic. Source: self-made

Social

For the social focus [9], the study aims to ensure, in time and space, both the coherence, acceptance, and preservation of the value system and the integration of the population, as well as the reduction of poverty and social inequalities, and overall, the harmonious coexistence and well-being of the population. A socially focused CPS aims to improve the living conditions of a social group, solve problems, meet needs, generate a positive impact across all sectors, and generally improve human activity. This includes considering the cultural, legal, and political aspects inherent in the environment where the CPS operates (Fig 10).

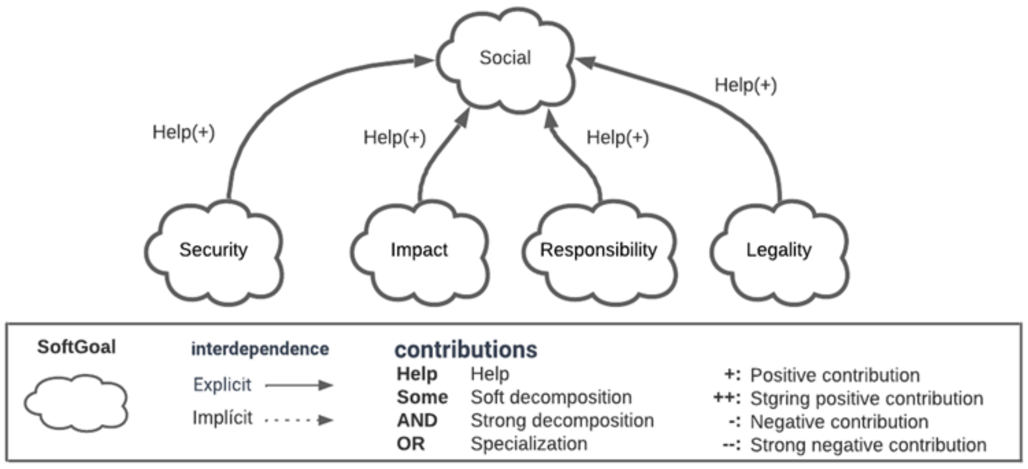


Fig 10. SoftGoal - Social. Source: self-made

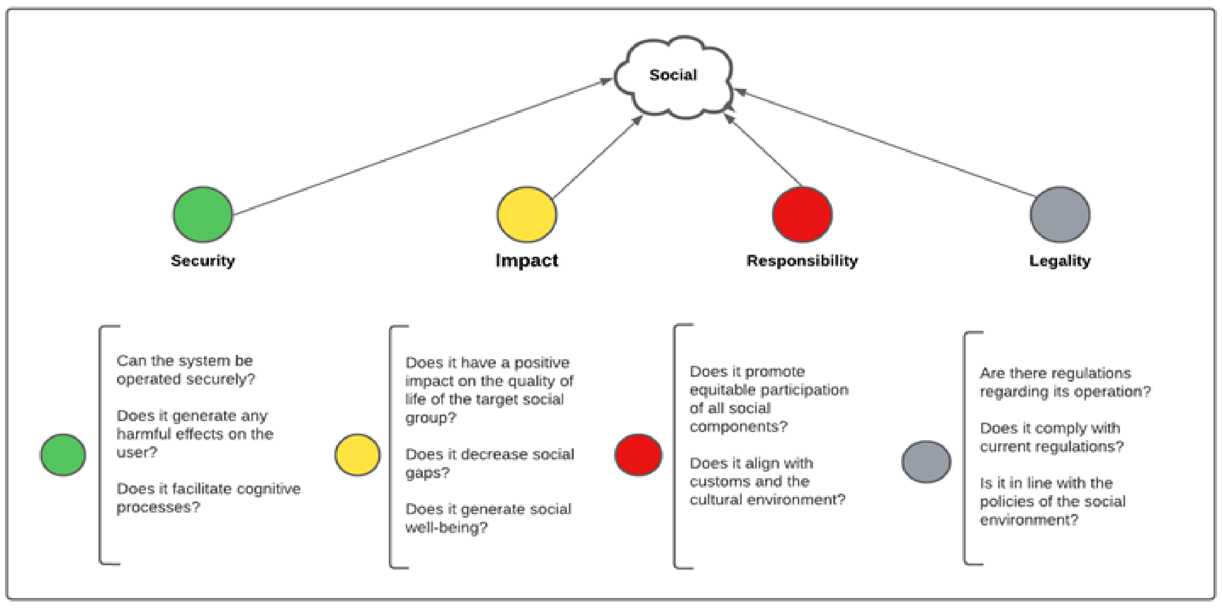
The following definitions are proposed, contextualized to CPS and our approach for the related second-level softgoals:

- Security: Established to protect the integrity of the system, its information, and its operation from unauthorized access and attacks. Additionally, it contributes to preventing potential consequences on individuals or users of the system[8].

- Impact: An indicator measuring the impact on the quality of life and well-being of the social environment related to the system[8].

- Responsibility: An indicator of ethical responsibility and the promotion of equity, participation, and common development. It relates to the relationship between the system and the cultural environment[8].

- Legality: An indicator of compliance with laws and regulations related to the system throughout its life cycle[8].



Can the system be operated securely?

Does it generate any harmful effects on the user?

Does it facilitate cognitive processes?

Does it have a positive impact on the quality of life of the target social group?

Does it decrease social gaps?

Does it generate social well-being?

Does it promote equitable participation of all social components?

Does it align with customs and the cultural environment?

Are there regulations regarding its operation?

Does it comply with current regulations?

Is it in line with the policies of the social environment?

Fig 11. Catalog - Social. Source: self-made

IV. MODEL EVALUATION USING FOCUS GROUP

First, it's important to emphasize that the evaluation primarily concerns the model itself, rather than the implementation of a specific example or practical case. To assess the proposed methodological model, we employed the Focus Group technique.

This technique involves assembling a group of professionals with expertise in the field to gather their opinions and obtain quantitative results. These results facilitate the identification of opportunities for improvement within the subject of study. We followed the guidelines outlined in [20] for conducting the focus group, which encompassed four distinct steps:

1. Objective planning and material preparation.

In this phase, the objectives of the focus group were defined as follows: to gather opinions on the aspects of the proposed model regarding its comprehensibility, applicability, suitability, and completeness; and, at the same time, to identify possible improvements. Following the guidelines defined in [20], the materials, procedural guide, mechanisms for socialization and formalization of documents, data capture and recording tools, and methods for analyzing the obtained results were prepared.

2. Recruitment of the focus group.

For the recruitment process of the participants and the definition of the main elements of the focus group [20], invitations were extended to engineers belonging to the research group in the field of sustainability at EAFIT University and professors from the Faculty of Engineering at the University of Quindío who work in software development and project management. Finally, the focus group was composed of professionals with experience and knowledge in different areas of software engineering.

3. Group session, collection of participants' opinions.

On the scheduled date and time, the agenda established for the focus group was initiated according to the previously defined execution protocol. Once the presentation of the proposal was concluded, 20 minutes were allocated for questions and interventions from the participants. After the question period, the validation questionnaire, designed to assess the proposal based on the four central aspects previously described, was shared with the participants.For the evaluation, the followingquestions were used:

3.1. Understandability:

P1. Do you consider the proposed model to be easily understandable?

P2. Do you find each of the SoftGoals to be easily comprehensible?

P3. Do you think the interdependence and contribution relationships between each of the proposed SoftGoals are understandable?

3.2 Applicability:

P4. Based on your experience, do you believe the SoftGoals defined in the NFR framework are appropriate and can be successfully applied?

P5. Do you think the effort required for the application of the NFR framework aligns with the expected results?

3.3 Suitability:

P6. Do you think the proposed SoftGoals are relevant for the analysis of sustainability in cyber-physical systems?

P7. Does the proposed model fulfill its main objective in the analysis of sustainability in cyber-physical systems?

P8. Is the proposed model considered a reference for projects related to cyber-physical systems?

P9. Do you find the interdependence and contribution relationships between each of the proposed SoftGoals appropriate?

3.4 Completeness:

P10. Based on your experience, do you consider the proposed model to be comprehensive for the intended objective?

P11. Does the generated assessment model provide the necessary elements for conducting a sustainability assessment of CPS?

P12. Does the proposed model offer elements that help identify improvement opportunities related to CPS sustainability?

3.5 Open-ended Questions:

P13. Do you believe elements (SoftGoals, relationships, contributions) should be added, removed, or modified in the proposal?

P14. Do you have any additional comments about the proposal?

4. Information analysis and results reporting.

Once the validation questionnaire was completed by the participants, the analysis of the obtained results was carried out. The rating scale ranged from 1 to 5, where 5 indicated complete agreement and 1 indicated complete disagreement. None of the aspects presented received a rating lower than 4; all participants provided responses with scores between 4(SomewhatAgree)and 5(CompletelyAgree) seeFig 12. Based on the results, we can conclude that the participants had a favorable opinion of the NFR-BASED FRAMEWORK FOR THE ANALYSIS OF SUSTAINABILITY IN CYBER-PHYSICAL SYSTEMS regarding the comprehensibility of the model, its applicability, suitability, and completeness.

	ScaleValue - Votes				
Question	**1**	**2**	**3**	**4**	**5**
P1					6 Votes
P2				2 votes	4 votes
P3					6 Votes
P4				2 votes	4 votes
P5				4 votes	2 votes
P6					6 Votes
P7				2 votes	4 votes
P8				1 vote	5 votes
P9				2 votes	4 votes
P10				1 vote	5 votes
P11				2 votes	4 votes
P12					6 Votes

Fig 12. FocusGroupclosed-ended questionsresults

Regarding the open-ended questions P12 and P13, the participants of the focus group expressed the following opinions:

- The SoftGoals are understandable as long as already has a background in systems; they can be adjusted to make it a bit easier for someone outside of this environment to comprehend.
- I believe over time, new SoftGoals associated with sustainability will be added. Therefore, it can be anticipated that the framework will scale with time.

Based on the results derived from the execution of the focus group, we can draw the following conclusions:

-The proposed SoftGoals are comprehensible to individuals with experience in systems, which is a positive outcome. However, suggestions were made to refine the content to enhance understanding for those not familiar with this field. Ensuring accessibility and clarity for a broader audience is crucial.

- Regarding potential adjustments or amendments, the responses indicate that current changes are unnecessary. Participants believe that the existing proposal effectively covers the project's scope. It is well-structured, sufficiently explained, and holds practical value for incorporating sustainability attributes into the development of cyber-physical systems.
- This positive feedback validates the robustness and significance of the presented proposal. Additionally, it emphasizes the perspective that new SoftGoals related to sustainability will likely be incorporated over time, aligning with the evolving nature of sustainability requirements in the realm of cyber-physical systems. The capacity to expand and adapt to emerging challenges and evaluation criteria is an essential attribute that ensures the proposal's continued relevance.

In summary, the collected responses not only underscore the proposal's relevance but also provide constructive recommendations to enhance its comprehensibility. Furthermore, participants' feedback suggests that the proposed NFR-Based framework has the potential to emerge as a valuable tool for evaluating sustainability aspects in cyber-physical systems. This outcome encourages further research and development in the field.

CONTRIBUTIONS

The research proposes a methodological framework that allows for the analysis and representation of the contributions of non-functional requirements (NFRs) within the context of sustainability in cyber-physical systems (CPS). This framework provides a structure for identifying, evaluating, and representing NFRs in relation to sustainability, facilitating informed decision-making during the design, implementation, and evaluation of CPS.

Focus on SoftGoals and Sustainability: The research focuses on SoftGoals related to sustainability, expanding the understanding of how the non-functional aspects of a system can contribute to its long-term sustainability. This includes environmental, social, and economic considerations in defining and fulfilling system requirements.

Utilization of the GQM-O Methodology: The research utilizes the Goal, Question, Metric - Operationalization (GQM-O) methodology as a basis for studying sustainability in CPS. This methodology provides a structured approach to defining goals, formulating questions, establishing metrics, and operationalizing indicators related to sustainability, improving the coherence and understanding of evaluation processes.

Practical Validation of the Proposed Framework: Through the execution of a focus group and gathering responses from system experts, the research validates the comprehensibility and relevance of the proposed methodological framework. The positive feedback received supports the effectiveness of the framework in addressing sustainability challenges in CPS and its ability to adapt to future evolutions in this field.

Identification of Areas for Improvement and Future Directions: The research identifies areas for improvement in the comprehensibility of the proposed SoftGoals, as well as potential extensions or additions of new SoftGoals related to sustainability. This provides a basis for future research and development in the ongoing evaluation and improvement of sustainability in CPS.

CONCLUSIONS

The presented methodology provides a structured and effective framework for evaluating and promoting sustainability in cyber-physical systems. The integration of non-functional requirements and the use of SIGs facilitate the specification, analysis, and evaluation of sustainability, enabling designers to make informed decisions to improve the environmental, economic, and social efficiency and impact of CPS. This methodology represents an important step towards the construction of more sustainable systems and contributes to the advancement of engineering in this ever-evolving field.

Through the proposed SIG, CPS designers can establish the core goals of the system based on sustainability, while also determining indicators for secondary goals. One of the most significant challenges in CPS design and implementation is accurately evaluating the degree of compliance with inherent non-functional requirements (NFRs).

While creating theoretical frameworks for sustainability analysis is a crucial objective nowadays, a major challenge lies in promoting the adoption of sustainable practices in system design and engineering applications in general. Sustainability should not be approached as a series of isolated elements, but rather as an interconnected set of characteristics that pursue a greater objective.

As future works, the methodology could be expanded and refined in specific organizational contexts, such as industries or particular social sectors. This extension would enable an understanding of how the methodology can be adapted and personalized to meet the specific needs and requirements of diverse environments or applications. Additionally, the inclusion of potential new criteria, metrics, or evaluation approaches would be considered. It would be crucial to instantiate a practical example that allows the application of the methodology in a real-world scenario. This example would serve as a case study to validate the effectiveness and applicability of the proposed model.

CRediT AUTHORSHIP CONTRIBUTION STATEMENT

C. Arce-Vargas: Conceptualization, Methodology, Validation, Formal Analysis, Investigation, Writing – Original Draft. **L. Restrepo-Gutiérrez:** Conceptualization, Methodology, Validation, Formal Analysis, Resources, Writing – Review and Editing, Supervision. **E. Suescún-Monsalve:** Conceptualization, Methodology, Validation, Formal Analysis, Resources, Investigation, Writing – Review and Editing, Supervision. **J. Aguilar-Castro:** Conceptualization, Methodology, Validation, Formal Analysis, Resources, Writing – Review and Editing, Supervision.

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