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A Method for an Integrated Sustainability Assessment of RFID Technology

Bartłomiej Gładysz ¹, Krzysztof Ejsmont ^{1,*}, Aldona Kluczek ¹, Donatella Corti ² and Stanisław Marciniak ¹

¹ Faculty of Production Engineering, Warsaw University of Technology, 02-524 Warsaw, Poland; bartlomiej.gladysz@pw.edu.pl (B.G.); aldona.kluczek@pw.edu.pl (A.K.); stanislav.marciniak@pw.edu.pl (S.M.)

² Institute of Systems and Technologies for Sustainable Production, Department of Innovative Technologies, The University of Applied Sciences and Arts of Southern Switzerland (SUPSI), CH-6928 Manno, Switzerland; donatella.corti@supsi.ch

* Correspondence: krzysztof.ejsmont@pw.edu.pl; Tel.: +48-22-234-81-28

Received: 25 July 2020; Accepted: 31 August 2020; Published: 2 September 2020



Abstract: Industry 4.0 (I4.0) has become a widely accepted manufacturing paradigm across a wide range of industries. It includes an array of various approaches, tools, techniques, and methods. They were known to researchers before, but when combined they build a new reality, which needs procedures for the assessment of technologies and manufacturing processes. Current assessment methods often fail to incorporate economic, environmental, and social impacts simultaneously in an integrated way. The potential implementation of a sustainability assessment procedure on a larger scale is seen for (well-developed) Radio Frequency Identification (RFID) technology. The measures for assessment were identified through a literature review and validated by expert panels. Validation measures were quantified using multi-criteria decision making (AHP). Criteria ranking was used for reasoning if the assumed modular structure responded to the experts' needs. To connect the existing research gap, a holistic and integrated assessment method for I4.0 applications, depicted in a structured way and tailored for RFID technology, is developed, which constitutes a research gap in current literature on this topic. Results showed that a modularized structure of approach (module—group of measures—measures [as indicators]) for RFID sustainability assessment, which depends on the complexity of this technology, may be a convenient method for assessment of I4.0 technologies. It was confirmed that all sustainability perspectives are important due to their contributions to supporting decisions and should be considered in the assessment of RFID. On the other hand, it can help managers and practitioners implement the assessment method in their practice to reduce pollution and save the environment.

Keywords: Industry 4.0; assessment of techno-organizational ventures; RFID; sustainability; technology assessment

1. Introduction

While the technological revolution called Industry 4.0 brings innovation at the manufacturing level, sustainability issues have exponentially risen as a crucial factor in manufacturing or industrial sectors [1,2]. However, for many companies economic results are still more important than the impact of their activities on the environment and society. Recent years have brought a start in attempts to change the current industrial and non-sustainable practices through Industry 4.0 (an example of this can be the Nobel Prize in Economics awarded in 2018 to William Nordhaus for findings deal

with interactions between society, the economy, and climate change) by using various assessment frameworks [2].

These changes are more visible for technology [3] than for other aspects of business activities. In large-scale industries or specific sectors technological changes are a challenge in implementation without an integrative or complex attempt to assess technology or Industry 4.0 applications.

In this context, there is the need to adapt sustainability assessment methods to the emerging production paradigms integrating economic, environmental and social concerns. UN sustainable development goals [4] and EU requirements related to “sustainable development” or “sustainability” (in manufacturing or industrial plants, sustainability means minimizing environmental effects (with conserving resources) and maintaining social equity simultaneously in economically-sound processes), environment protection, and corporate social responsibility have also been considered to play an increasingly important role in promoting these concepts. Sustainability is “the quality of being able to continue over a period of time” [5] in terms of financial, environmental, and social performance. Operationalization of sustainability practices is still an important issue for professionals [6]. Historically, traditional sustainability assessment methods in the pre-Brundtland era were mainly based on the triple bottom line issues (economic, social, and environmental) treated separately, starting with environmental issues [7] by assessing, e.g., resource consumption, pollution, and their impact or focus on one specific topic only (economic or environmental concerns) [8]. This paradigm was gradually extended by many researchers and practitioners to integrate with other approaches (e.g., economic and environmental) [9] rather than focusing on using a standalone widespread approach like Life Cycle Analysis (LCA) [10]. This tool essentially tackles identification, quantification, and minimization of the environmental impact over the whole life cycle of a product (system) [11]. Other technology assessment methods were also investigated. Medić et al. [3] presented a hybrid method integrating the Fuzzy Analytic Hierarchy Process (FAHP) and PROMETHEE for assessing advanced technologies in manufacturing companies in the context of Industry 4.0. Another insight into the researching assessment framework based on integrated multiple criteria decision-making was performed by Ocampo et al. [12], employing it in logistics. Gladysz and Kluczek [13] developed a modern industrial approach presenting the sustainability evaluation indicators framework for RFID systems.

Among the several technologies that are impacted by new trends and publicity is Radio Frequency Identification (RFID), which gained popularity in many business sectors due to a relatively wide range of its applications [14] and logistics advantages (benefits) in different business, e.g., in transportation/distribution, health care systems, and many industrial sectors as well as functional areas of organizations, e.g., production logistics, warehousing, external supply chains. The functionalities of the RFID technology and its applications were described in the study [15]. Its public acceptability in turn is manifested in enabling consumers to make sustainable choices in their purchases (through using a RFID system) to inform about the carbon footprint of purchased products and implementing the technology management system (TEM) in place, which can serve as a way to communicate about technology with consumers (and the entire society).

The advantage of RFID systems (compared to other identification techniques and technologies, e.g., commonly used barcoding), is that many objects can be detected automatically and almost simultaneously without visual contact [16]. Some of the reported benefits of RFID applications include less incorrect machining, decrease of cycle times leading to shorter lead times, less inventory shrinkage, and more accurate inventories (lower stock and lower out of stock occasions).

Although economic benefits of RFID were proved [14], there has been a wide discussion on how to assess benefits and the associated costs (in terms of economic efficiency) of RFID initiatives. A question remains of how to assess RFID benefits in economic, environmental, and social terms. Moreover, some economic benefits lead to the environmental benefit, e.g., lower stock means lesser transport operations means lower air pollution, CO₂ emissions, use of resources, etc. Apart from its advantages, RFID has some environmental disadvantages (waste generation and impact on human health, certain materials in the environment), as it falls under the Restriction of Hazardous Substances and Services

(RoHS 2002/95/CE) regulation regarding environmental issues as well as economic concerns (e.g., unit costs of tags are relatively high compared to barcodes).

Tags, which become waste when disposed, are made of materials that are hard to recycle. Cell phones may present similar health risks at their disposal stage [12]. Tags often assume the form of hard tags (in plastic cases) or inlays/labels (plastic + paper + metal), and consequently cause several problems in recycling plants due to materials included in these devices [17].

Although there has been some progress towards achieving sustainability in many industrial sectors, they still miss RFID-oriented sustainability assessment methods. Despite the identified benefits of RFID technology (which are restricted to technical possibilities and related economic impacts), there is an area for assessing this I4.0 technology from sustainability perspectives. This assessment will be carried out in a structured way, integrating measures in terms of the triple bottom line in the manufacturing domain. RFID technology was chosen to illustrate the proposed method because it is relatively well-known to the wide audience in different industries. RFID itself has not created the full landscape of I4.0. However, it should be considered as an important part of it. RFID enables gathering many data on identification of objects and times of movements from various processes. It fosters a high degree in the automation of identification. Therefore, RFID creates big data sets which could serve it both for real-time decision making, forecasts and simulation modeling based on real data. This opportunity coined together with other I4.0 technologies, such as big data, creates a huge potential for improvement actions along a wide variety of businesses. In addition, permanent access to such extensive information provides manufacturing companies with a new scheme of doing business.

The integrated approach for assessing RFID sustainability can improve sustainability performance. Moreover, the presented assessment methodology framework needs to be tailored to specific requirements dependent on a specific technology used. It can also vary performance results across different applications of the technology. Using sustainability goals and their features to set assessment measures for technology might have a positive industrial impact on achieving sustainability. The incorporation of the assessment approach allocates various resources to efficiently and effectively enhance the productivity and reduce operation costs of industrial companies. It allows enterprises to achieve better resource management.

The technology assessment helps to assign resources to specific operations and manage task schedules to ensure that the right resources are ready to complete a given operation at the right time. Resource optimization for the environment can be achieved through circular economy practices, which aim at leveraging the overall sustainability of the organization “through the implementation of closed loops and regenerative and restorative physical and economic cycles and the combination of maintenance, repair, reusing, refurbishment, remanufacturing and recycling processes” [18]. The RFID technology is a significant industrial contributor to the economic growth of many countries, but, at the same time it leads to environmental pollution. RFID systems are composed of hardware and software. The hardware part of the RFID system is being considered as electronic waste; it consists of different materials (plastic, metal) and is impossible to recycle due to problems with the separation of materials. Assessing the sustainability of RFID has an impact on the utilization of resources to manufacture RFID hardware. It helps to reduce unnecessary redundancy of the RFID system, such as excessive hardware. This leads to preserving resources used to manufacture RFID hardware.

Therefore, this case study may provide motivation for developing a new approach to evaluate the technology, where its decisions can contribute significantly to the company’s sustainability performance through applying possible measures and sub-measures in terms of various categories. The industrial sector differs widely in RFID deployment. If RFID assessments developed, they found specific applications in various industrial environments and were used for very different purposes (e.g., in health care, fertilizers, etc.). Current assessment methods based on life cycle analysis often fail to incorporate economic, environmental, and social impacts simultaneously in an integrated way [19]. The LCA-based methods, including LCA, environmental Life Cycle Costing, and Social Cycle Assessment (SLCA) are used as the best applicable at a process level. The subjective character of

these methods and the lack of information on quantifiable measures as stated by many researchers are major problems in RFID assessment. Unfortunately, the characteristics of various methods, although acknowledged by many researchers in the industrial sector, are rarely found in the RFID technology. Due to flexibility in the usage of sustainability assessment methods, there is still potential to be combined with the well-developed or inspired by other methods such as modular, technical project evaluation (IMATOV) to assess holistically RFID systems where TBL sustainability will be embodied. The proposed method also provides development of more precise (sub)measures influencing the company's processes.

Therefore, an integrated assessment of RFID holistic integrated assessment considering economic, environmental, and social concerns is missing in the scientific literature and practice. The designed method demonstrates the research boundary to the IMATOV-based sustainability assessment framework, including RFID technology.

The novelty of the paper against related works rests in the identification of (sub)measures and assessment of RFID tailored to its specific needs in industrial practice in order to enhance sustainability. The paper contributes to meeting the research aim of how sustainability assessments of RFID should be holistically integrated and impacted on a company's performance. In order to achieve the goal, the research questions are as follows:

- What are the measures of the impact of the RFID system on the performance of the company's processes in terms of sustainability in economic, environmental, and social dimensions;
- what is the importance of each measure of the impact of the RFID system on the performance of the company's processes in terms of sustainability.

Due to the novelty of the research, there exist managerial challenges in determining and planning resources by means of RFID assessment. Another advantage of this research over other ones is the focus on three sustainability concerns presenting the environmental, economic, and social concerns of the considered technology separately, although the method is treated as an integrated approach.

The aim of this paper is to present a new integrated sustainability approach for RFID technology assessment inspired by a modular and holistic method for techno-organizational ventures. The method is RFID-oriented in terms of goals of the lower levels of measures, but the highest level is useful for any Industry 4.0 technology that needs social and environmental considerations, i.e., it is useful for the full set of I4.0 technologies. To fill the research gap, the idea of the proposed approach in this article is to include and integrate a wider scope of simple and complex measures (e.g., inputs, outputs, resources in metric units) supported by pure techno-organizational parameters as well as social and environmental metrics of the system.

2. Literature Review

2.1. RFID Sustainability-Oriented Assessment

Many concepts, methods, and approaches are developed for sustainability evaluations of specific technologies, processes, products, or activities [20–22] often categorized as analytical and procedural analysis [20]. In this section, various methods are discussed with respect to their coverage of sustainability dimensions (environment, economic, and social) for technology. From the procedural perspective, Environmental Technology Assessment (EnTA) methodology focuses on specific and broader potential impacts of a technology on the environment, and even the entire life cycle of a technology from just a primarily qualitative point of view, considers technology and its potential impact “on the environment, having cultural and socio-economic consequences” for sustainable development.

Although in recent years various methods and approaches for sustainability assessment have been developed, most of them (e.g., EIA) incorporate environmental and economic concerns while neglecting social issues (EIA). One method, Environmental Extended Input Output Analysis (EIOA)/Hybrid LCA, solely integrates social aspects, such as employment [23]. These methods framed in the Life

Cycle Analysis (LCA) were developed on the basis of “environment in general”. This concept is to “focus on environmental issues with policy, program and infrastructure provision”. The first attempt to expand the LCA framework through integration and connection with other methods was carried out by [20]. Later, LCA methods attempted to address social and economic issues in addition to environmental concerns, but in a piecemeal manner. Leach et al. [24] extended LCA beyond narrow, conventional forms of technology assessment to allow a broader social appraisal of the alternative-pathways to sustainability. Kluczek [25] discussed the integrative sustainability concept, which combines the disaggregation analysis based on LCA with the quantification of environmental and socioeconomical sustainability impacts from technologies. In this approach, the sustainability assessment of technologies was combined with a life-cycle approach (LCA and LCC) [20,21]. Combined LCA-LCC can be useful to evaluate environmental and economic aspects in life terms by assigning a price to different production/operations elements. However, LCA is a product-oriented tool (not a technology-, or system-oriented tool) for the assessment of environmental implications. The integration of sustainability and EIA takes place at three levels: (1) the conceptual addressing with a framework that depicts links between sustainability and impact assessment, (2) the regulatory redefining the intent and scope of EIA requirements, and (3) the applied integrating sustainability into each step of the EIA planning process. It does not consider economic impacts formally. Lawrence [26] proposed the integration of sustainability and EIA at three levels: (1) the conceptual addressing with a framework that depicts links between sustainability and impact assessment, (2) the regulatory redefining the intent and scope of EIA requirements, and (3) the applied integrating sustainability into each step of the EIA planning process.

A more sophisticated approach in the sustainability approach is Life Cycle Sustainability Assessment (LCSA) that combines standalone life cycle assessment techniques already in use, LCA, LCC and Social Life Cycle Assessment (SLCA) addressing the triple-bottom line paradigm in a complex way [27]. Effective LCA is based on a range of different indicators. Unfortunately, LCSA “requires improvement through the enhancement of life cycle methods or by support drawn from multi-criteria decision tools (MCDA)” [28]. Achieving sustainability requires that LCA focus on whole ecosystems with a shift away from a product point of view, including also the technology point of view. The most important ecosystem parameter is the magnitude of the environmental effect, which typically depends on the amount of waste per unit area. Despite the complexity of its form, LCA must consider the technologies where industries are operating and the areas that provide resources for that industry. Such a function area must be used for the emission source. In the economic and social dimensions, there is still a need for consistent and robust indicators and methods. Thus, having a methodology to assess the impacts from various resources that were used during production processes is useful to combine with other methods. Other available assessment tools such as Cost Benefit Analysis (CBA) [29] and Material Flow Analysis (MFA) [30] require high-level expert competence.

Another view of assessment is directed to a system dynamics approach to technology sustainability assessment, discussed by [31]. It was suggested that systems dynamics is the best approach for technology sustainability assessment while considering policy interventions. This approach is dedicated to macro-level (national and international) technology sustainability. Therefore, it is not suited for an assessment of a technology from the micro perspective of a company.

The discussed approaches to sustainability assessment of technologies could be categorized as:

- General methods which cover the policy making level mostly;
- methods suited for specific technologies.

Therefore, it was necessary to find or develop a method that could be easily suited for the considered technology. No method from the above categories provides such an opportunity for assessing RFID. Therefore, it was decided to review literature on the sustainability of RFID in general (not necessarily concerning assessment problems) and seek a method of assessment (not necessarily focused on sustainability originally) that could be suited to the needs of considered technology.

Sustainability issues are often strictly interrelated (e.g., environmental and social issues), but might be contradictory in some cases, e.g., a lesser number of RFID tags (lesser waste) are related with lesser inventory accuracy. From the social perspective, environmental disadvantages (waste, pollution, and gas emissions created) may be linked with health risk. There is also a vivid discussion about privacy and security concerns related to RFID [32].

The study involved a literature review on methodologies for the assessment of RFID sustainability in various sectors [13,33]. Gladysz and Kluczek [13] presented the results of the analysis of 53 papers related to “RFID sustainability” limited to fragmentary aspects of sustainability or specific application areas, i.e., a specific sustainability dimension (e.g., environmental), the impact (mostly positive) of RFID applications on the sustainability of the improved system (e.g., air luggage), the specific industry (e.g., fresh food supply chain) or the sustainability of RFID system in categories of its production (manufacturing of RFID hardware), waste generated, energy consumed during production, etc.

The first attempt to evaluate RFID-based systems was made using LCA in terms of environmental concerns [34], recently showing a positive impact on environmental sustainability. As a result of many years of sustainability assessment research, for example, Denuwara et al. [33] described environmental, economic, and social impacts of using RFID in the apparel value chain, stressing out a source of waste and investment cost. More focus was put on the social perspective of RFID assessment in the same industry, when considering tagging finished goods delivered to consumers or checking the carbon footprint of the purchased product, or solutions for foods and drugs traceability that minimizes waste and health risks [13]. Gladysz and Kluczek [13] adopted social indicators accepted in the study [19] to check their applicability in RFID systems. This social impact was measured by three indicators covering the whole life cycle of RFID systems through measuring (i) public acceptability; (ii) safety; and (iii) human health effects from external air quality. Another study deployed RFID to enable traceability in manufacturing, providing a real-time view through production processes and operations [16].

However, these described in [13] are fragmentary approaches and they lack modular structuring based on the techno-organizational characteristics of the assessed system and wholeness. This holistic approach, although based on the triple bottom line paradigm [35], i.e., economic, environmental, social issues, results from the lack of a relationship between them in order to find crisp boundaries. Van der Togt et al. [36] presented a literature review of RFID environmental impacts in the healthcare setting. In the same sector, Fisher and Monahan [37] described social impacts which are strongly affected by staff surveillance concerns and systems’ breakdowns, leading to a higher workload of employees. Social impacts are approached mainly as threats from consumers’ privacy point of view [32]. However, it is also proved that RFID systems could also impact (mainly positively) consumers’ shopping, leisure, and conferences experience (e.g., [38]). Social impacts are also very closely related with environmental ones, e.g., a RFID solution to check the carbon footprint of the purchased product, RFID applications to study habits of animals (e.g., in entomology, ornithology, or farming) or solutions for foods and drugs traceability (minimizes waste and health risks).

Hence, the social concern may include air pollution from energy consumption that can have an adverse impact on human health. It can measure CO₂ emissions from energy consumption of manufacturing and installing of RFID systems. In turn, safety is mostly related to occupational health and accident performance along the technology life cycle and this is improved through RFID applications [19]. RFID systems should be also assessed for privacy and surveillance threats, which are very specific issues in many RFID systems. An increase in labor intensification could be another issue to be analyzed. The air pollution aspect could be also quantified. However, its estimation is very difficult, as it would require the participation of the systems’ manufacturer, systems’ integrator, and systems’ user. Therefore, this indicator may be rarely applied.

Much effort was devoted to develop approaches, tools, and related sustainability-oriented indicators that might be integrated into the overall consistent sustainability assessment method in manufacturing [39]. Gladysz and Kluczek [13] proposed to assess RFID from two contrary environmental perspectives, i.e., as the source of new waste (e.g., tags are electronic waste) and the

decrease of inefficiencies (such as excessive stocks, transportation, overproduction, etc.). It is still needed to assess what amount of waste is generated yearly (tags, readers, etc.) and what is the scope of the system (number of circulating tags, readers, coverage, etc.). It is also proposed to assess the duration of tags' lifecycle, the number of reads in a lifecycle, the number of supply chain echelons, and reading points, etc. as the hardware may be exploited with different intensity. It is assumed that the more intensive the exploitation is, the more economic benefits are delivered by generated waste (disposed hardware). Second, a decrease of other waste such as like shrinkage, excessive inventory and transportation, or low utilization of assets should be assessed as a positive environmental impact. Such an approach considering both the positive and negative environmental impact of RFID systems is missing in the literature and industrial practice.

RFID can enhance environmental sustainability by providing more transparency to an organization's green supply chain management practices [14]. In contrast, the manufacturing process of the RFID tags' antennas influences negative environmental impacts and even toxic effects [34]. Though interest in the topic has been growing over the last years, only a few researchers decided to treat papers on RFID sustainability in a holistic way. None of the reviewed papers beside just a few offer an integrated method for assessing the sustainability of RFID technology while considering environmental benefits and costs, economic benefits and costs, or social positive and negative impacts. In the present day, standards providing sustainability requirements, specifications for implementing RFID, and their assessment framework are still missing. Therefore, a detailed framework to assess the sustainability of the RFID system incorporating the triple bottom line paradigm is needed. It applies to any I4.0 technology at its first level, but RFID is a very evident example, which was chosen as a case in this article. Considering all relevant, afore-mentioned considerations and potentials from the RFID applications throughout various industrial areas as well as the literature on this topic, the approach to be developed will be focused on defining measures and indicators for the quantification of various sustainability impacts of RFID systems.

The proposed method integrates all TBL sustainability concerns (economic, environmental, social) in order to answer the research questions:

- What are the measures of the impact of the RFID system on the performance of the company's processes in terms of sustainability in economic, environmental and social dimensions;
- what is the importance of each measure of the impact of the RFID system on the performance of the company's processes in terms of sustainability.

This research investigates the design of the method to assess sustainability for RFID considering economic, environmental, and social measures based on the RFID case. An integrated method for assessing sustainability of RFID is necessary for increasing the productivity of any manufacturing company using (or considering) RFID. For the proposed assessment method for RFID systems, it is critical to present how this study identified the variables. The only study found that tackled problems of identification of a broad set of measures was [13]. However, it lacks modularity and is not a holistic approach. Therefore, the set presented in [13] was considered as a starting point for defining measures. This set was later confronted with opinions of experts through expert panels and participatory observations. Details of the identification of measures are presented in Section 3.3 separately for each module.

2.2. Integrated Assessment of Techno-Organizational Ventures

This section presents a conceptual methodology of technical project evaluation (IMATOV) which has been chosen as an inspiration for integrated assessment of RFID [40,41]. It proposes an assessment framework that allows for evaluating the effects of the implementation of a techno-organizational venture (project, process, etc.), then mapping a full set of quantitative and qualitative changes in an organization and results of its activities [40]. IMATOV was originally developed for the evaluation of

technical and organizational projects of flexible automation [40], but it shows flexibility in adaptation to modern challenges (e.g., technology assessment) [41,42].

The mentioned modification may relate to manufacturing, innovations, maintenance, and results of organization activities such as goods and/or services. The basis of IMATOV consist of eight modules defined as sets of measures grouped according to the scope, degree of analytics, and indifference to external factors. These modules dedicate three main processes (Figure 1): (i) design of manufacturing production services; (ii) innovation (investments and modernization) and (iii) exploitation of outputs from manufacturing. Some components such as fragmented (sectional) simple measures (FSM), fragmented (sectional) complex measures (FCM), synthetic measures (SM) belong to the first process; measures of investments (MI), measures of effects (ME), preferential investment assessment (PIA) and indifferent investment assessment (IIA) belong to the second process and techno-operational parameters (TOP), and synthetic measures belong to the third one.

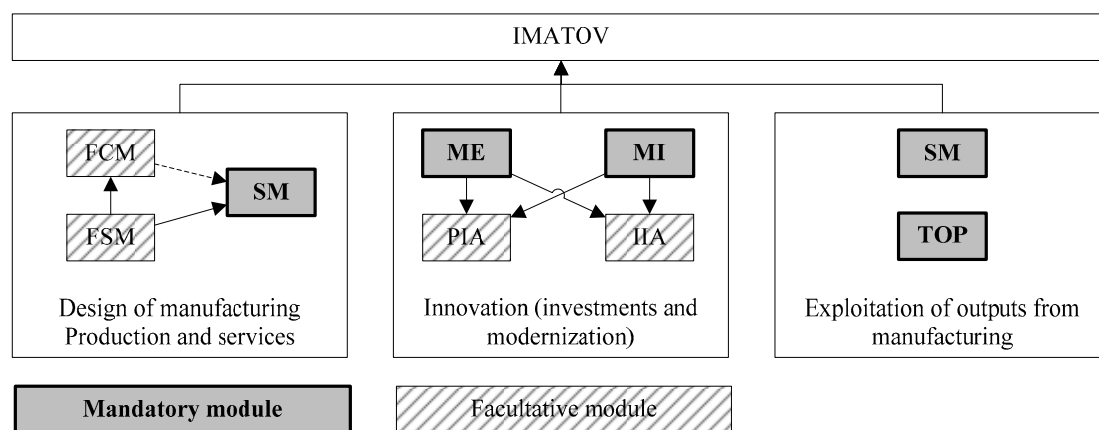


Figure 1. The conceptual methodology of technical project evaluation (IMATOV)'s modular structure based on [40].

A given set of detail measures is assigned to each module. Marciniak [40] proposed a three-stage water-fall-like approach for a design of details of specific IMATOV application (Figure 2). Ejsmont [42] presented a modified IMATOV based on the holistic assessment of “intelligent” technologies. This approach was a trigger to be employed in RFID assessment towards sustainability. However, the proposed method was not oriented on specific characteristics of RFID. Therefore, the goal of this research is to detail the method in order to present a new approach based on modification of the IMATOV, which is RFID-oriented and tailored (specifically in terms of measures). When inspiring the IMATOV, it seems that the leading elements that condition the construction of the evaluation are [41]: (i) the approach to evaluation according to the binding paradigm in economy and management; (ii) the definition of the impact area on soft, technical, and organizational aspects of the projects that are under evaluation, which may change due to economy development and globalization; (iii) successive changes of criteria and measures regarding the selection of management methods or techniques, due to the necessity to consider the behavior of environment, which is characterized by fast changes and a growing global character.

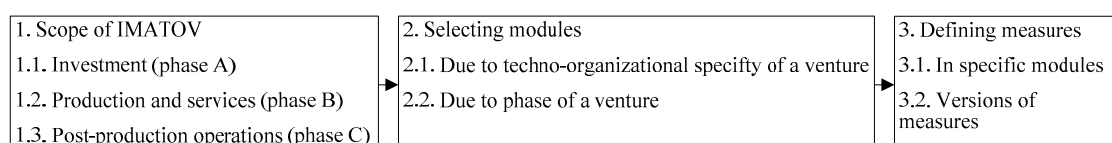


Figure 2. IMATOV phases based on [40].

The benefits of IMATOV and its strengths in comparison with other methods which constituted the decision criteria to choose this approach to assessment include:

- Complexity;
- relative easiness of measuring complex processes;
- sequential nature of the assessment process (three levels: holistic view—modules—measures);
- openness, allowing for including human and social factors;
- flexibility and adaptability, allowing for maintaining compatibility with other legacy assessment systems.

On the other hand, there also exist weaknesses in relation to the adopted paradigm of an assessment that include difficulties with considerations of specificity of a solution, getting enough detailed assessment, a lack of quantitative benchmarks for measured values. However, these problems could be avoided by redesigning IMATOV and shaping it accordingly with the specificity of considered technology, i.e., RFID in case of this research. An additional advantage of the method is the ability to link different groups of measures and the ability to impart them with specific weights, depending on the company's management.

Concluding on IMATOV, it was chosen due to the following reasons:

- It is transparent and modular, so the assessment is consistent and transparent as well;
- it is flexible and universal, so it can be adopted to almost any problem just by choosing modules and measures appropriate to its structure and assessed problem;
- it enables holistic approach and is not just reductionist, i.e., one measure can play different roles in different modules, e.g., a decrease of the carbon footprint is positive for environmental dimension, but it can have directly associated costs in an economic dimension impacting negatively on cash flow;
- it is easy in application, requires no additional training for staff, nor support from experts;
- it enables easy customization by assigning weights to modules and measures, some unimportant criteria could be skipped purposely;
- it incorporates all the TBL dimensions of sustainability;
- it could be easily supported with other methods (e.g., controlling, AHP);
- it is dynamic and the assessment could relate to different periods, as values of measures are changing.

3. Integrated Method for Sustainability Assessment of RFID Systems: Proposed IMAR Framework

3.1. Methodology

The exploitation of RFID by a company could be considered as a specific form of techno-organizational venture in one of its basic stages, i.e., design, implementation, exploitation/maintenance. IMATOV is the method designed for a techno-organizational venture that allows for modifying its structure accordingly with specific needs and requirements related to the project, technology, system, and organization under investigation. It was already proved that IMATOV applications deliver valid results under various including “intelligent technologies” [42,43]. RFID should be discussed as an intelligent technology. Therefore, a distinct modification of IMATOV can be discussed as a starting point to develop an integrated method for sustainability assessment of RFID systems (IMAR).

“In order to meet the three determinants (triple bottom line—author's note), one needs to take into consideration the fact that evaluation of technical projects should follow a holistic approach, be comprehensive and integral” [41]. A holistic approach is the one following the Aristotelian paradigm of precedence of the whole over portions. The whole is not equal to the sum of its parts. In addition, RFID projects are restricted to recognizing technical possibilities instead of assessing sustainability, leaving much of the potential to implementing IMAR in production sectors [14]. Therefore, a comprehensive

approach is the one addressing a full set of characteristics of the assessed structure. Integrality is enabled when the assessment reflects links between elements of the assessed system. The proposed holistic paradigm laying under the assumptions of IMATOV is very important to assess RFID systems in terms of the triple bottom line perspective (economy, environment, society) [13].

The methodology of presented research which led to the development of an integrated method of assessment of RFID (IMAR) is illustrated in Figure 3. The procedure of IMAR is depicted in Figure 4.

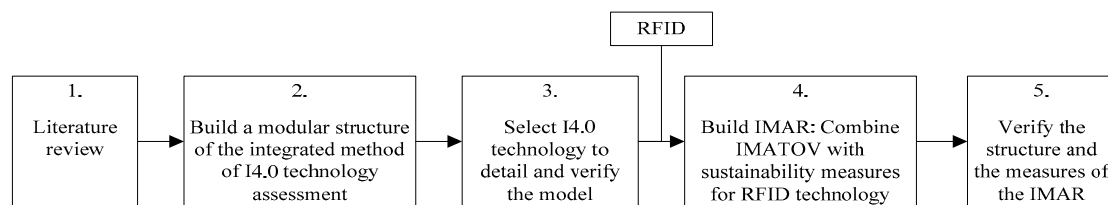


Figure 3. Methodology.

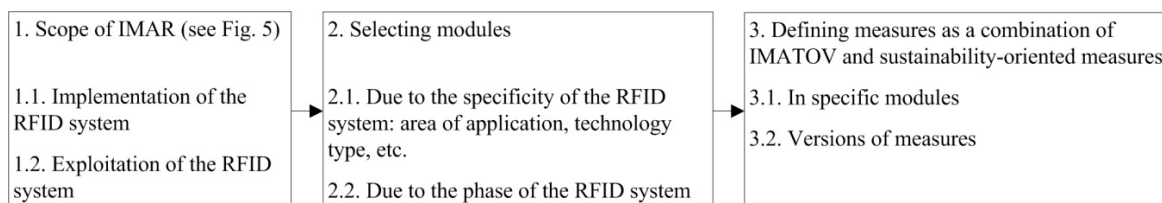


Figure 4. Integrated method of assessment of RFID systems (IMAR) procedure.

The structure of modules known from IMATOV analyses was adopted and supplemented with additional modules oriented on sustainability issues. The designed approach is universal on its highest level and its modular structure could be applied for the assessment of any technology implementation or exploitation. RFID is often chosen since it is relatively a well-known and widely discussed technology to verify such an approach. The next step is to find RFID specific measures within each assessment module. The last step verifies the IMAR which is based on an expert panel and multi-criteria ranking of modules and measures (approach using Analytic Hierarchy Process).

Knowing the characteristics of IMATOV, the authors approached its modifications in order to enable a holistic assessment of RFID systems, which was identified as a research gap. This section presents a high-level structure of the model including the adapted set of modules and their links. It addresses the aim of identifying impacts of an RFID system on the performance of the company.

Accordingly, with the design procedure for an IMATOV application (see Figure 2), the proposed modification considers: (1) the scope of IMAR (Figure 5); (2) the selection of modules (i.e., FSM, FCM, SM, TOP—Figure 5) due to a specific nature of considered technology and a phase of assessed venture; (3) the design of measures and their versions (see further sub-sections of this section).

3.2. Scope and Modules in IMAR

The scope of IMAR depicted in Figure 5 may be considered in three variants, i.e.,

- design and implementation of the RFID system (an analogy for joint Phase A and Phase B of IMATOV),
- exploitation of the RFID system (an analogy for joint Phase B and Phase C of IMATOV), and
- both previously mentioned (joint assessment of implementation and exploitation phases of the RFID system).

Marciniak [41] suggested that “the integrated method has two main features, which encourage to adopt it, such as complexity and the organized choice of measures according to the rules of modularized structure”. A module performs a specific function. It is a set of measures that may be transformable

into a set of other measures with the same function but featuring a different structure. For example, one fragmented simple measure for a construction project could be the number of cranes, which is not applicable for IT software implementation. Therefore, other measures should be used depending on the characteristics of the considered project. Modules' adoption requires a precise analysis of its relations to other modules. The structure of the modified integrated method of assessment of RFID systems (IMAR) is presented in Figure 5. This involves using modules known from IMATOV and supplementing them with an additional module dedicated to social and environmental parameters.

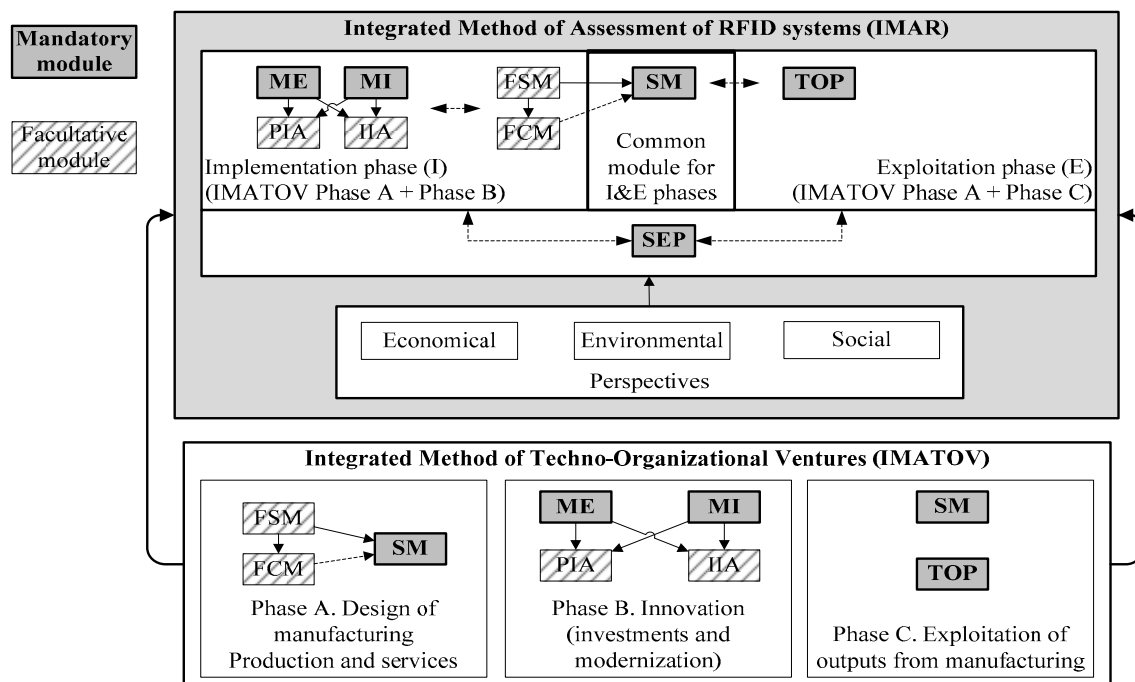


Figure 5. IMAR modular structure built upon IMATOV modules.

The SEP module (social and environmental parameters) is an extension of original IMATOV as proposed by [41] for technology evaluation using IMATOV. Measures from the SEP module may be classified as fragmented sectional and complex measures. However, including the measures in FSM and/or FCM is reasonable only when there are relatively few measures of this type. If classified separately due to the importance of sustainability in the modern economy, it should be noted that it affects and is affected by other modules (Figure 5). It is rational to classify these measures separately due to the goal of having a presented framework (for a sustainability assessment), which makes this module the one with many measures included.

3.3. Measures in IMAR

3.3.1. Fragmented (Sectional) Simple Measures (FSM)

The first module is Fragmented (Sectional) Simple Measures (FSM) and includes a set of measures that describe basic inputs to the RFID system. This module includes measures expressed in natural units (e.g., pieces, kilograms, meters, etc.). A list of possible measures categories to be included in this module are: FSM1: IT hardware, FSM2: software infrastructure, FSM3: other assets, FSM4: human resources, FSM5: skills, FSM6: trainings, FSM7: wages, FSM8: total resources consumption, FSM9: wastes, FSM10: privacy threats, FSM11: logistics parameters. Each category can, in turn, be organized in a tree-like structure. Table 1 provides examples of detail measures for the FSM1 category. Each of the mentioned measures may be further split into several types of measures, e.g., the number of fixed

readers of a specific type (FSM1.1.1.x), number of tags of a specific type (FSM1.6.1.x), lifecycle of tags of a specific type (FSM1.6.3.x), etc.

Table 1. List of possible measures and sub-measures to be included in the category FSM1.

FSM1: IT hardware	FSM1.1: fixed readers FSM1.1.1: pieces; FSM1.1.2: monetized value
	FSM1.2: antennas FSM1.2.1: pieces; FSM1.2.2: monetized value
	FSM1.3: cabling FSM1.3.1: length; FSM1.3.2: monetized value
	FSM1.4: mounting and fixtures FSM1.4.1: pieces; FSM1.4.2: monetized value
	FSM1.5: mobile readers FSM1.5.1: pieces; FSM1.5.2: monetized value; FSM1.5.3: lifecycle
	FSM1.6: tags FSM1.6.1: pieces; FSM1.6.2: monetized value; FSM1.6.3: lifecycle (not durability)
	FSM1.7: tagging levels FSM1.7.1: number of levels used; FSM1.7.2: names of levels: unit, containers, returnable assets, etc. according with GS1 standards
	FSM1.8: employed standards and frequencies
	FSM1.9: servers
	FSM1.10: desktops FSM1.10.1: pieces; FSM1.10.2: monetized value
	FSM1.11: value of hardware
	FSM1.12: number of operations
	FSM1.13: operational time for equipment

The list of possible measures and sub-measures to be included in the category FSM2 is the following: FSM2.1: estimated lines of code, FSM2.2: features of software, FSM2.3: use case scenarios, FSM2.4: entities, FSM2.5: database size, FSM2.6: number of legacy systems, FSM2.7: number of employed technologies.

The FSM 3 group of measures is dedicated to other assets which are necessary for operations of RFID systems, but are not directly included as RFID hardware. It may include computer desktop stations, computer mobile terminals e.g., mounted on forklifts.

The FSM4 group of measures may include workers in total or workers in specific job categories (e.g., business analyst, software engineer, middle level manager, line workers, etc.) measured in full time equivalents, etc.

The FSM5 group of measures may include lists of necessary and lacking skills in predefined categories.

The FSM6 group of measures may include the number (in events, in hours, in man-hours, etc.) of training sessions related to lacking skills (see FSM5), training sessions for workers who will use the system (in events, in hours, in man-hours), etc.

FSM7 may include the wages of staff who will use the systems in total or in specific categories, etc.

The FSM8–FSM10 groups of measures are discussed in detail in the SEP (social and environmental parameters) module.

The FSM 11 group may include measures such as: unit times of identification (FSM11.1), lead times (FSM11.2), inventory levels that are in pieces and monetized (FSM11.3, FSM11.4), and out of stock levels (FSM11.5).

3.3.2. Fragmented (Sectional) Complex Measures (FCM)

FCM is a set of measures that describes relations between basic economic characteristics of typical RFID systems. Measures in this module were developed based on participatory observations in approximately 50 implementations of RFID systems in a variety of organizations (libraries, manufacturing, logistics, courts, energy supplies) and processes (volumes circulation in libraries, internal logistics in manufacturing and warehousing, rail transportation, inventory). The measure was selected if at least five final users of the observed RFID systems were interested in it. It should be noted that one may generate a large number of FCM measures by combining FSM measures, but only a few relations are of interest for system users. Examples of measures and sub-measures are included in Table 2.

Table 2. List of possible measures and sub-measures to be included in the category Fragmented (Sectional) Complex Measures (FCM).

FCM1: work intensity and equipment utilization	FCM1.1: coverage and scope of the system (percentage of units tagged)
	FCM1.2: manual scans per day per worker
	FCM1.3: automated scans per day per reader
	FCM1.4: scans per day per tag
	FCM1.4.1: manual scans; FCM1.4.2: automated scans
	FCM1.5: fraction of automated scans in the total number of scans
	FCM1.6: number of handheld readers per worker
	FCM1.7: utilization time for equipment type (operational time per total available time)
	FCM1.8: no. of devices per tagged objects tags in circulation) FCM1.8.x: per specific equipment type
FCM2: experience	FCM1.9: fraction of identification unit times in total lead time
	FCM2.1: RFID experience per worker in calendar units
	FCM2.2: trainings per workers
	FCM2.2.1: in events; FCM2.2.2: in hours

3.3.3. Synthetic Measures (SM)

SM is a set of measures which holistically characterizes RFID systems and its results, i.e., different categories of costs, benefits, e.g., unit costs, the total income, etc. “They should pay particular attention to the level and character of the technical solution e.g., through diverse taxation of the financial result which, as a result, defines the profit level” [41].

SM may include groups of measures proposed in Table 3. An extensive discussion of synthetic measures was presented by Gladysz and Kluczek [13], who placed them under the economic category (the other two were environmental and social according to the triple bottom line paradigm). Due to the focus of the presented approach, the measures of a synthetic nature related to the environmental and/or social aspect are classified into the SEP module, e.g., energy consumption, unemployment rates, injuries, etc.

Table 3. List of possible measures and sub-measures to be included in the category Synthetic Measures (SM).

SM1: cost measures	SM1.1: operating costs: SM1.1.1: in total; SM1.1.2: hardware in total; SM1.1.3: for category x; SM1.1.4: of waste treatment
	SM1.2: maintenance costs SM1.2.1: in total; SM1.2.2: hardware in total; SM1.2.3: for category x
	SM1.3: cost of resources SM1.3.1: cost of electric energy; SM1.3.2: cost of resource x
	SM1.4: unit cost of system exploitation SM1.4.1: per tagged object; SM1.4.2: per scan operation; SM1.4.3: per tagged object; SM1.4.4: per worker
	SM1.5: costs of disposed hardware SM1.5.1: readers; SM1.5.2: tags; SM1.5.3: others

Table 3. Cont.

SM2: benefit measures	SM2.1: decrease in cost of working capital's freezing SM2.1.1: monetized decrease of inventory levels; SM2.1.2: monetized decrease of lead times
	SM2.2: monetized decrease of inventory handling costs
	SM2.3: monetized decrease of out of stock values
	SM2.4: decrease costs in actions (e.g., incorrect deliveries effected from incorrect identification)
	SM2.5: unit monetized benefits SM2.5.1: per tagged object; SM2.5.2: per tag in circulation; SM2.5.3: per reader; SM2.5.4: per worker
SM3: effectiveness measures	SM3.1: cost/benefit related measures SM3.1.1: unit benefits minus unit costs (unit profit); SM3.1.2: unit profit per tagged object; SM3.1.3: unit profit per identification operation; SM3.1.4: unit profit per reader;
	SM3.2: profitability measures SM3.2.1: return on assets; SM3.2.2: return on investment (and/or IRR, NPW, payback period)

3.3.4. Techno-Operational Parameters (TOP)

TOP is a set of measures that characterize technical and operational performance of the assessed technology, e.g., functionality, universality, durability, reliability, availability, breakdowns, interoperability, etc. This set of measures describes software and hardware IT infrastructure technical and operational parameters. TOP groups of measures may include such categories like: read rates (TOP1), durability of equipment (TOP2, e.g., TOP2.1—handheld readers, TOP2.2—fixed readers, TOP2.3—tags), shock resistance e.g., a drop from 2 m on any side (TOP3), equipment dimensions (TOP4), equipment weight (TOP5), water and dust resistance, e.g., for an IP class (TOP6), latencies (TOP7), software and hardware reliability measures (TOP8, e.g., TOP8.1—availability of server, TOP8.2—mean time between failures, etc.), interoperability with other systems in the supply chain (TOP9), interoperability with global standards (TOP10), reading distances (TOP11), easy scalability, integration, modification (TOP12), memory of tags (TOP13), operating and storage temperatures (TOP14), tags optimization (on metal, neutral) (TOP15), frequency range (TOP16), aesthetics (shape, colors, etc.) (TOP17), features of tags (TOP18), attachment options (TOP19), battery (for active tags, capacity, lifecycle, etc.) (TOP20), reader features (e.g., antenna ports, GPIO ports, power consumption, etc.) (TOP21).

3.3.5. Social and Environmental Parameters (SEP)

Measures in this module were developed analogically as for the FCM module (see Section 3.3.2), i.e., based on participatory observations in circa 50 implementations of RFID systems in a variety of organizations (libraries, manufacturing, logistics, courts, energy supplies) and processes (volumes circulation in libraries, internal logistics in manufacturing and warehousing, rail transportation, inventory). However, after considering the lower awareness of social and environmental factors compared to of economic ones, the number of interested users decreased to one. The measure was selected if at least one final user of the observed RFID systems was interested in it. The other angle for the selection of measures in this module was a review of literature related to environmental (mainly waste generation due to new equipment as a negative factor, and issues related to more transparent logistics as positive factors) and social impacts of RFID (mainly privacy concerns as negative factors and better working conditions as positive factors). Tags and readers are impossible to recycle and very hard to dispose and remanufacture, because they are electronic devices composed of different materials (plastic, metal, batteries) [17]. Even if technologically it would be possible to pursue these sustainable options, doing so is not economically reasonable. Closed-loop systems generate a smaller need to buy new tags yearly. If tags circulate in a closed loop, then less waste is generated. It is also always better if

tags are used in several echelons of a supply chain (multiple reads in multiple identification points). Benefits are achieved multiple times while waste is generated only once.

The module of social and environmental parameters (SEP) is a set of measures that characterize the influence of the RFID system on the mentioned parameters. Measuring such impacts should ensure the proper state of the society and environment in the future. Groups of measures in the SEP module may include total resources consumption (SEP1 = FSM8), waste (SEP2 = FSM9), privacy threats (SEP3 = FSM10), reductions of employment (SEP4), workers' energy expenditure (SEP5), other ergonomics factors (SEP6) etc. Considering the goal of the designed framework, it is advised to classify these listed measures into the SEP module instead of having them under the FCM or FSM umbrella, as those are broad and numerous sets of measures. However, this decision should be based on a specific case and assessment needs.

SEP1 and SEP2 groups may be split based on a type of resources, e.g., kWh of used electrical energy (SEP1.1), number, weight, and value of disposed tags (SEP2.1.1, SEP2.1.2, SEP2.1.3), number, weight, and value of disposed electronic devices (SEP2.2.1, SEP2.2.2, SEP2.2.3), other types of waste (SEP2.3, e.g., plastic, paper, metal, dangerous materials, etc.), rates of waste utilization and processing (SEP2.4). An extensive list of social and environmental parameters for the RFID system in manufacturing was presented by Gladysz and Kluczek [13]. The list is manufacturing oriented; however, it may be easily adapted for any RFID system. Other parameters to be considered include public acceptability, safety and health issues (air pollutants, accidents), and waste reduction.

3.3.6. Other Modules

Other modules include measures related with investment issues of RFID systems implementation, i.e., (from least complex): measures of investments (MI), measures of effects (ME), indifferent investment assessment (IIA), preferential investment assessment (PIA). Measuring investment is a relatively routine task. It comprises such issues as estimating investment in hardware and software supplies, testing and installation. Measuring effects is a relatively more challenging task. However, there is available literature related to RFID system effects measurements and estimation, based on case studies [44], simulation modeling [45], cost-benefit models [46]. Having investments and effects measured, one may easily calculate some indifferent investment measures (e.g., payback period) and preferential investment measures (e.g., IRR, NPV, ROI). Other indifferent investment measures (e.g., the investment duration period) may be obtained through scheduling and budgeting methods. The RFID system may be considered as a specific type of IT system. Therefore, RFID-related investments may be evaluated using evaluation methods and tools dedicated for IT investments [47]. The procedure for modules' design and selection of measures was discussed in [41,42].

4. Results and Discussion—Validation of the IMAR Framework

In order to validate the model, specific procedures should be applied:

- A real industrial example of RFID application was chosen to apply the IMAR framework;
- expert panels were chosen as a technique to collect opinions about the importance of modules within IMAR;
- multi-criteria decision making (i.e., AHP) was used to quantify opinions;
- criteria ranking was used for determining whether the assumed modular structure responds to the experts' needs.

For the validation of the IMAR procedure, it was necessary to qualitatively assess the structure of IMAR and to collect field data on the importance of modules and measures. Both these issues could be addressed by one method, which is the expert panel. The AHP was chosen for the development of criteria ranking, as it is one of the most popular forms of MDCM because it is easy to use, requires no additional training for experts, and enables qualitative pairwise comparisons that are easily quantified

later. Therefore, the AHP does not require the collection of detailed data and through pairwise comparisons makes experts more willing to provide their opinions (judgements).

The proposed integrated method for sustainability assessment of RFID systems was illustrated, taking as a reference the industrial example presented in [13,48]. The IMAR framework was verified for its usefulness on the case of dynamic spaghetti diagrams supported by the Real Time Locating System [48]. The Analytic Hierarchy Process [49] was used to estimate weights of criteria for decision making (see Table 4) and ranking of alternatives by pairwise comparisons. Three alternative solutions were considered. None of them was preferable over other ones at a first glance, especially after considering the sustainability aspect. Therefore, decision makers faced a decision problem that can be summarized to the choice of the most sustainable solution of the set of considered systems. The AHP-OS application was used for the computational procedure [50]. Three alternatives [51] (Alt1—Passive UHF RTLS, Alt2—Active Wi-Fi RTLS, Alt3—Active UWB RTLS) were assessed by two experts experienced in RFID deployments (with 10 years of experience in managing, designing, and analyzing over 50 deployments). For the decision hierarchy based on the IMAR approach, the results of global priorities of criteria were obtained using a standard linear scale (Table 4). The choice of modules for the assessment was driven by the phase of technology lifecycle within the analyzed company, i.e., the implementation phase. The overall consistency ratio (CR) was lower than 10% for prioritizing criteria (4.4%) and there was no CR for any level greater than 8.6% (mostly 0%). Therefore, judgements were assumed to be consistent.

Criteria rankings for IMAR modules and measures were obtained using group AHP and AHP-OS software. Two experts were employed in pairwise comparisons. It was decided to gather data from only two experts due to their great and wide experience in RFID implementations (over 50 implementations as project managers, solution designers, and business analysts in a variety of businesses and processes including volumes circulation in libraries, rail logistics, internal logistics in manufacturing and warehousing, and inventory in energy providers and courts). Analyzing the results obtained in Table 4, the highest weight at level 1 was assigned to the PIA module (42.9%). The method was depicted in the structured way including the selection of RFID specific measures in FSM, FCM, TOP, and SEP modules. FCM and FSM modules (facultative in the IMAR model) were neglected by experts as not being necessary for the considered case due to sufficient data being delivered in the SM module. The experts indicated that FCM and FSM modules are more relevant for the assessment oriented on purely engineering and technical aspects of RFID systems. The weights of the other modules are in the range 11.5–16.8%, so they are similar. This confirms the opinion of experts that the economic perspective is still the most important for many companies (at least for the ones cooperating with experts). The payback period obtained the largest global priority among the various measures (34.3%) and was considered to be much more important than ROI (80/20).

The other highest measure weights were also related to finance: MRO costs (11.2%), hardware investment (9.8%), ROI (8.6%). It is worth noting that all measures from the SEP module obtained a very low global priority. This was examined due to the fact there are more groups of measures and individual measures on subsequent levels (from 2 to 5) and all of them have been assessed as being fairly equal. The experts assessed environmental and social perspectives as being equally important. In the social perspective, the most important group of measures was “Safety & health” and in the environmental perspective, the most important individual measures were “Electronic devices disposed completely” and “Decrease of stocks in units”. The results of a SEP global weight compared to global weights of the other module suggest that the SEP module should not be neglected, and it was assessed by the experts as being similarly important to ME, MI, and SM.

Table 4. Decision hierarchy for analytic hierarchy process (AHP)-calculations.

Level 1	Level 2	Level 3	Level 4	Level 5	Global Priority
ME 11.5%	Labor efficiency: 50.0%		Decrease of cycle times (average): 6.5%		0.4%
			Lead time (average) decrease: 33.6%		1.9%
			Increase of worker productivity: 19.9%		1.1%
			Decrease of errors: 40.0%		2.3%
	Inventory accuracy: 50.0%		Decrease of costs of frozen stocks: 20.0%		1.2%
			Decrease of stocks in monetary values: 20.0%		1.2%
			Decrease of costs of inventory handling: 20.0%		1.2%
			Decrease of shrinkage in monetary values: 20.0%		1.2%
			Decrease of costs of shrinkage handling: 20.0%		1.2%
MI 13.1%		Software investment costs: 25.0%			3.3%
		Hardware investment: 75.0%			9.8%
SM 16.8%		MRO costs: 66.7%			11.2%
		Disposed hardware yearly costs: 33.3%			5.6%
PIA 42.9%		ROI: 20.0%			8.6%
		Payback period: 80.0%			34.3%

Table 4. Cont.

Level 1	Level 2	Level 3	Level 4	Level 5	Global Priority
SEP 15.7%	Environmental: 50.0%	Waste generation: 50.0%	Amount of waste: 75.0%	No. of tags disposed completely: 18.6%	0.5%
				No. of tags circulating in the system: 8.4%	0.2%
				Electronic devices disposed: 53.4%	1.6%
				Electronic devices installed: 19.7%	0.6%
			Lifecycle & supply chain integration: 25.0%	Tags lifecycle duration in supply chain: 43.1%	0.4%
				No. of tags reads in its lifecycle: 32.3%	0.3%
				No. of reading points in a supply chain: 15.9%	0.2%
				No. of supply chain echelons benefiting RFID: 8.6%	0.1%
		Waste reduction: 50.0%	Inventory accuracy: 50.0%	Decrease of stocks in units: 75.0%	1.5%
				Decrease of shrinkage in units: 25.0%	0.5%
			Assets utilization: 50.0%	Decrease of paper documents: 8.3%	0.2%
				Decrease of printing accessories: 4.4%	0.1%
				Decrease of number of assets: 8.2%	0.2%
				Decrease of the total value of assets: 14.1%	0.3%
				Decrease of fuel consumption in liters: 28.3%	0.6%
				Decrease of electricity consump. in kWh: 36.6%	0.7%
	Social: 50.0%	Public acceptability: 33.3%	Qualitative assessment of customers’ choice: 13.0%		0.3%
			TEM in place: 6.9%		0.2%
			Qualitative assessment of threats by users: 22.6%		0.6%
			Additional staff: 39.8%		1.0%
			Relations improvement: 17.8%		0.5%
		Safety & health: 66.7%	No. of occupational accidents: 50.0%		2.6%
			Air pollutant: 50.0%		2.6%

The assessment aims to indicate the most sustainable solution by considering selected criteria and taking the IMAR modular approach as a reference for the evaluation. Three alternative real time locating systems were assessed using the linear scale. Their technological and organizational details were described in [49,51]. The resulting ranking confirmed previous rankings reported in [13,51], i.e., alternative 3 was superior to alternative 2, which was superior to alternative 1 (priorities using the standard linear scale: Alt3—54.3%, Alt2—25.7%, Alt1—20.0%, with $CR_{MAX} = 9.0\%$). Priorities obtained in [13], also using AHP approach to the ranking, were 43.9% for Alt3, 32.9% for Alt2, and 23.2% for Alt1 ($CR_{MAX} = 8.9\%$). There were other scales [50] applied for calculations and the ranking was not dependent on the scale applied (Table 5). However, judgments using the adaptive, inverse linear, and power scale are significantly inconsistent.

Table 5. Ranking of alternatives considering sustainability using the IMAR approach.

Scale	Group Results			CR_{MAX}
	Alt1	Alt2	Alt3	
Standard linear	20.0%	25.7%	54.3%	9.0%
Logarithmic	3.9%	30.2%	46.0%	4.1%
Root square	24.7%	31.0%	44.3%	2.2%
Inverse linear	24.2%	31.2%	44.6%	17.0%
Balanced	22.4%	30.1%	47.5%	6.2%
Balanced generalized	21.6%	29.3%	49.1%	2.3%
Adaptive balanced	20.2%	27.9%	51.9%	8.3%
Adaptive	18.7%	22.1%	59.1%	13.0%
Power	18.4%	15.6%	66.0%	30.3%
Geometric linear	16.4%	18.2%	65.4%	5.6%

This was the reasoning behind neglecting the FCM and FSM module (facultative in the IMAR model) by the experts. However, the experts indicated that FSM and FCM may play an important role (FSM mostly informative, but FCM also controlling role) when more complex solutions are implemented. It was shown that both approaches (presented in this paper and in [13]) for sustainability assessment, however employing different criteria hierarchy (IMATOV based modules here, and TBL in [13]), deliver the same rankings as the pure technology-oriented selection process reported in [51]. The referred pure technology-oriented selection performed using TOPSIS delivered the following relative closeness measures: 0.256 for Alt1, 0.537 for Alt2, and 0.770 for Alt3.

Reflecting on research questions formulated in Section 2.1, the IMAR framework was developed in order to enable holistic sustainability assessment of the RFID technology. The details of the framework constitute answers for research questions, i.e.,

- The set of modules and measures for the assessment of the impact of the RFID system on the performance of the company's processes in terms of sustainability economic, environmental, and social dimensions was defined (see Section 3.3) based on a literature review and participatory observations;
- the ranking of measures was developed based on expert panels and AHP pairwise comparisons; FSM and FCM modules were neglected by the experts, who pointed out that the SM module is sufficient for technical assessment, and MI, SM, and PIA modules are important from the economic perspective; the SEP module was also considered as being important, which confirms the need for holistic assessment considering all TBL pillars (the economy, environment, and society).

5. Conclusions

A novel decision aid method based on sustainability assessment was proposed. The resulting model can be applied in the manufacturing sector as an important driver to aid in the shift towards sustainability by achieving triple-bottom-line objectives [35] when RFID is implemented. The method is based on the hierarchy model that starts with modules and finishes with specific measures. The method based on the step-by-step procedure starts with the definition of modules and finishes with the definition of the specific measures (see Figure 4). Besides the aforementioned factors, the method includes key measures indicating the fact that these measures are both important for meeting sustainability principles and relatively easy to assess for whoever is the assessor (the company, provider, authorities, or consumers).

It should be emphasized that the importance of the topic discussed in the article is growing rapidly. Even though the IMAR framework is focused on the RFID technology, analogical problems are somehow also raised for other technologies. This is due to the high intensity process of implementing new technologies in the era of Industry 4.0: Internet of Things, Cyber-Physical Systems, Sensors & Actuators, Data Analytics, Automated Identification/Location, etc. The presented framework could be applied at its level 1 for any I4.0 technology. It could be easily adjusted for I4.0 technologies (other than RFID) just by identified specific measures at levels subsequent to level 1 (see Table 4). The integrated method for assessing this type of solution should adopt a paradigm that assumes the balance of the economy, environment, and society. Such an approach is also in line with the principles of sustainable development, as well as the concept of corporate social responsibility. Therefore, it is fully justified to develop a universal, integrated method for assessing this type of solutions and to implement it in practice.

The advantages of the developed method include: comprehensiveness; transparency; sequential order of the assessment process (three stages, i.e., adoption of the holistic approach: module—group of measures—measures); openness which fosters direct consideration of human and social factors in the assessment; and high flexibility and easy adaptability, which allows for compatibility with other evaluation systems. It is necessary to emphasize the novelty of the developed solution, which is the modification of the integrated assessment method [40–42] by adding new structural modules, as well as creating a list of measures tailored to the needs of assessing a particular Industry 4.0 solution (RFID). Until now, the use of the AHP method to select weights and create a ranking of alternatives by pairwise comparisons has not taken place.

The results suggest that the PIA module should become mandatory for at least the RFID technology assessment. In the experts' opinion, for many companies the economic perspective is still the most important (at least for the ones cooperating with the experts). It was also shown that the SEP module is considered by the experts as an important one since it gained comparable importance with regard to all the other modules excluding the PIA, which was the most important one.

The results obtained in this article can be very useful for many groups of recipients. The potential advantage of the proposed method is linked to the overall companies vision which the IMAR provides, e.g.,

- companies will be able to assess the sustainability for investment in a given technology instead of a pure profitability assessment available through the use of single measures,
- technology providers will be able to work on its further development and improvement in terms of achieving sustainability, and
- companies will be aware of the benefits and technical risks of a given solution.

The proposed framework can serve as a managerial tool for any organization, but specifically industrial ones, which would want to assess an I4.0 technology implementation holistically. The presented framework was filled with RFID technology specific measures. However, the highest level of the framework (see Table 4, level 1) is useful for any type of technology. This is specifically the

case of Industry 4.0 technologies, which need careful social and environmental considerations, as they create many opportunities, but also threats (especially social ones like a fear of unemployment, etc.).

The research has developed the integrated assessment method for Industry 4.0 technology (Table 4, level 1), illustrated on the RFID case (Table 4, levels 2–4) to deliver future perspectives on:

- analytical analysis in terms of the identification of sustainability assessment indicators system, applicable in an industrial environment,
- conducting sustainability-oriented project decision making for a greater sample size of companies,
- enabling data input for further risk simulation and modeling to monitor it in real case studies.

On the other hand, the potential of the developed method and its associated risk were not discussed, providing implications for managers. They should assess potential risks that can be exploited if risk is accepted by them and addressed consciously.

The implementation of the model requires involvement of decision-makers to arrange techno-organizational structures according to the triple bottom line. In this way, the changes could allow managers to understand the dynamics of technical projects facing challenges of sustainability and based on this fact to make decisions that assess sustainability of technology in terms of economic, environmental and social concerns.

In this volatile environment, companies should intend to make systematic analysis reasoning to make decisions that improve not only technology but also in-house processes, e.g., production or logistics. Indicators-based decisions have in turn an essential impact on sustainability in three perspectives.

Although the goal of the paper was achieved, the research is characterized with some limitations. The research problem discussed in this paper has not been completely solved and verified in industrial practice. Another limitation is the openness of the list of measures in individual modules, and the lack of validation of the proposed assessment for other technologies of Industry 4.0 due to the lack of industrial data. The limitation of this research is a validation procedure considering only the opinions of two experts. This will be built upon in further research by the inclusion of a larger group of experts. However, the goal of experts' assessments was just to demonstrate the applicability of AHP and the procedure itself, rather than to provide a set of ready to use criteria priorities. Criteria priorities could be developed by practitioners themselves when applying the IMAR method. Currently, measures are insufficient coincident with the sustainability I4.0. Therefore, further research should be undertaken. First, the values of individual measures which were unambiguously determined should be quantified, while calculations for partial and total assessments in numerical values need to be expressed both at the level of the modules and the entire system. Second, the method used for calculating the relationship between the modules and measures also requires refinement. For this future goal, it is recommended to verify other methods and tools, e.g., Data Envelopment Analysis (DEA). Third, a consolidation of obtained assessments and the development of a formula allowing for unambiguous interpretation of the results should be also taken into consideration. Common method biases may impact on the reliability and validity of research [52]. Fourth, a specific focus of the research should be put on managing the project's/technology's risk due to exposed risk from market shifts. By using the model, managers would be able to predict incoming industrial trends and adjust their enterprises to still changing regulations in a quick manner. It is also an opportunity to look for new markets and changes in current business models. As a consequence, they can be dealt with along with uncertainty at the strategic decision making level.

On the other hand, this developed method provides a set of sustainability indicators that could be applied to other technology assessment or organizational-venture projects. It in turn, becomes necessary to explore this method to balance the applicability and completeness of sustainable coverage.

The delivered decision model could be used in a wide scope of production engineering, especially in manufacturing systems. It is recommended to validate the results of the research based on a bigger

sample of industrial companies on the condition that the developed assessment model is accepted to a greater extent. This may allow for comparing different sector-specific insights.

The issues raised from the point of view of sustainability of Industry 4.0 seems to be so huge that further attempts to develop a comprehensive assessment method for this type of ventures will be examined in the future.

Author Contributions: Conceptualization, B.G.; methodology, B.G. and S.M.; validation, B.G., K.E., A.K. and D.C.; formal analysis, B.G., K.E., A.K. and D.C.; investigation, B.G., K.E., A.K. and D.C.; resources, B.G.; data curation, B.G. and A.K.; writing—original draft preparation, B.G. and K.E.; writing—review and editing, B.G., K.E., A.K. and D.C.; visualization, B.G.; supervision, B.G.; project administration, B.G. and K.E. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by Polish National Agency for Academic Exchange under grant No. PPI/APM/2018/1/00047 entitled “Industry 4.0 in Production and Aeronautical Engineering” (International Academic Partnerships Programme). The APC was funded by the Polish National Agency for Academic Exchange.

Acknowledgments: We would like to thank the anonymous reviewers for their comments that allowed us to further enhance the outcomes of this research.

Conflicts of Interest: The authors declare no conflict of interest.

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