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Toward an Improved Monitoring of Engineering Projects

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***Abstract*—With the growing economic pressure, one lever for companies to be competitive is to efficiently monitor projects. To this goal, the different processes involved in the project must be carefully supervised and the project manager needs to be well-informed on their state and progress to take the best decisions thanks to accurate performances of indicators, process, and project. Another key factor of successful decision-making in engineering projects beyond taking into account information from the project manager on the project management (PM) is to consider information from the systems engineer on the product development. This paper proposes a process to monitor engineering projects relying on a set of project performance indicators that integrate the views of both project manager and systems engineer. This process includes three main activities: 1) defining project performance indicators related to the processes described by international guides and standards; 2) valuating and weighting these indicators by consulting project managers and systems engineers; and 3) constructing a hierarchical framework of indexes to support project monitoring. This proposal thus refers to the practices described in PM and systems engineering norms and improves them by involving project managers and systems engineers into decision-making, with the goal to take more coherent decisions.**

***Index Terms*—Decision-making, monitoring, performance indicators, project management (PM), systems engineering (SE).**

I. Introduction

BECAUSE companies operate in a highly competitive international economic environment, they are continually seeking to improve project management (PM) performances and practices. Some studies note that a lack of or a limited collaboration in industry has resulted in major project failures, such as excessive delays and high rework costs, all of which make companies less competitive [1], [2]. To improve product performances, reduce costs and increase stakeholders' satisfaction, companies need to optimize their engineering processes [3].

Many recommend that collaborative engineering should play a more significant role in companies [4], [5], but true collaboration is hard to implement. As Roschelle and Teasley [6] pointed out, many people often call collaboration what is more a matter of cooperation, that is defined as "a division of labor among participants as an activity where each person is responsible for solving a portion of the problem." People often mention collaboration meaning compromise or consensus-building. However, this already constitutes a first step toward improving practices in companies. For instance, currently, there are few if any opportunities for engineers to be involved in the decision-making process. As such, there is a need to investigate how to better integrate inputs from different stakeholders (project managers, systems engineers, customers, etc.) into decision-making processes in companies [7]. Indeed, stakeholders of a project have different and often divergent interests [8]–[10]. For example, one could caricaturally say that project managers focus on cost and time [11] while systems engineers are generally more concerned with product performance than cost. However, cost, time, technical performance, etc. as well as many others parameters, are important to consider, perhaps at different levels of importance according to the phase of the project, to monitor the project. In any cases, having a better knowledge of the systems engineers and project managers points of view will help making more informed decisions [12]. This involvement of engineers in decision making would contribute to bridging the gap between the engineering and management activities usually organized in silos in companies [13], thus resulting in a better coordination during projects and increasing the chances of success for the project.

The objective of this paper is therefore to enhance the monitoring of an engineering project during its entire life cycle by defining a monitoring process, called cooperative monitoring process that provides project managers with a wider and less subjective view on the project progress that integrates the systems engineers' view. In this proposal, project managers and systems engineers, that play major roles in engineering projects, are encouraged to cooperate and share their vision to better lead the project toward its objectives in terms of cost and delays but also in terms of technical performance.

Section II is a state-of-the-art survey that stresses the need to bridge the gap between project managers and systems engineers in engineering projects. Section III introduces our

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proposal of cooperative monitoring process. The illustration of key stages of this process will be given in Section IV. Section V develops a case study and Section VI concludes and provides suggestions for future research.

II. Research Status

Integrating PM and systems engineering (SE) became an important stake for researchers and professionals quite recently [14]–[17]. Some studies address the question of integrating PM and SE but usually focus on some technical issues such as security, energy or mechanics [18]–[20]. Some addressed systems engineering [21], [22] or software design platforms [23], [24] but few of them extend their scopes to consider issues related to system design, such as the impact of the choice of components on system architectures or the simulation of behavioral specifications, or to project monitoring. This state-of-the-art analysis outlines the need to overcome the drawbacks and weaknesses of current practices.

Considering tools, companies have either built or bought various tools to supervise product design or to monitor projects in order to improve project performance [1]. However, no tool currently provides an integrated vision of both [25]. Some tools consider integrated views such as Cockpit [26], ENOVIA [27], or unified planning [28]. The PM officer usually uses dedicated basic PM tools such as Microsoft Planner and other specific tools [29]. Thus, a survey made with a panel of local companies mentioned that they have encountered problems in managing projects, including difficulties to assess the states of projects and to detect and prevent deviations during project progresses [14].

However, in complex systems development, the most important issue is how to balance time, cost, and performance [30]. To control cost overruns, each one must understand that decisions they make impact the other [11]. Given that system design and performance strongly impact cost, managers, and engineers have many sources of conflicts of interest which directly affect system delivery and project profitability [14]. These difficulties explain why improving procedures and aligning practices can lead to considerable gains in project performance and product quality. Innovations are necessary to improve coordination [31]. This paper is thus founded on the obvious need to integrate PM and SE in project monitoring and control. The problem we address is that of a cooperative management of multitechnology systems projects throughout the system life cycle, involving multiple stakeholders, to ensure that they all work toward the same objective, designing the "right product" for the end user, keeping costs and deadlines under control. Our proposal aims to offer a solution to the following hurdles.

1) PM and SE are complementary disciplines but they are implemented separately.
2) Project progress evaluation is traditionally considered with a managerial perspective and less concerned with technical perspective.
3) Decision-making processes are generally driven by the project manager while other stakeholders can be ignored.

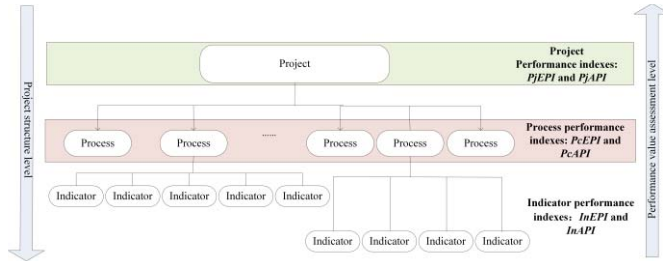

Fig. 1. Three evaluation levels.

III. Cooperative Monitoring Process

Effectively monitoring projects is critical to the project success. Monitoring a project means collecting, recording, analyzing, reporting information concerning project progress, and making decisions to lead the project so that it reaches its target. Our proposal focuses on how to monitor project progress by integrating inputs from project managers and systems engineers.

A. Overview of the Proposal

We propose a cooperative monitoring process that can be used throughout the whole project life cycle. This process is part of a wider strategy aiming at improving the chances of project success [32]. In [33], we developed a framework to align processes defined in the international PM and SE references and defined performance indicators associated to these processes. This paper completes this framework by defining a cooperative monitoring process based on this framework.

Regarding the moment when the project managers evaluate the project progress, Rosenau and Githens [34] and Lauras *et al.* [35] pointed out the trend for project managers to try to circulate a single report between many different recipients. They considered that this is a mistake because senior managers will look for summary status and forecast data, whereas middle managers will look for more specific and tailored information on operational details. They stressed the necessity to have a system of performance indexes which allows visibility of project progress at different levels as well as ensuring coherence between these views. We thus propose a hierarchal framework of performance indexes for evaluating the project progress has been defined, as shown in Fig. 1, with three levels of indexes: 1) project performance; 2) process performance; and 3) indicator performance indexes. A detailed definition of these indexes will be provided in Section III-B.

Referencing to the international PM and SE references, the framework is organized in an indicator level, a project level, and a process level. At the process level, one or several indicators (e.g., cost, duration, resource, etc.) can be associated to each process. Different performance indexes can be elaborated from these indicators, to give the different levels of managers a more or less detailed view on the project progress; these indexes are aggregated from bottom to top.

The process is cooperative in the sense it involves stakeholders that have different roles within a project, e.g., project managers (red) in Fig. 2 and systems engineers (blue), in evaluating the project progress based on these performance indexes

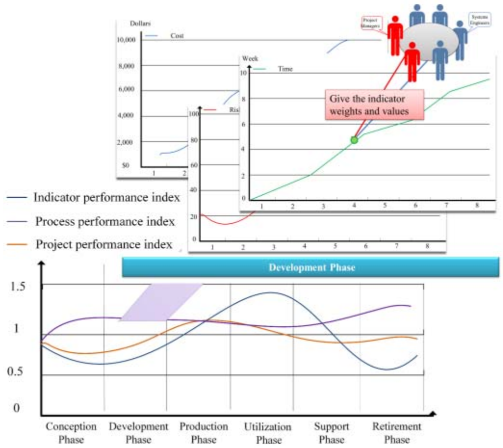

Fig. 2. Overview of the methodology.

and in its monitoring; these stakeholders take part in assigning indicators' values and weights. This allows a natural alignment of practices and points of view (PM and SE ones in this case but the method covers a wider range of stakeholders profiles), by integrating the values and weights given for indicators by the different stakeholders, thanks to the analytic hierarchy process (AHP) method, a technique for organizing and analyzing complex decision that has particular application in group decision making.

The cooperative monitoring process consists of four principles.

1) Definition of indicators by different stakeholders.
2) Definition and evaluation of the indicator indexes and weights.
3) Definition and evaluation of the process indexes and weights.
4) Definition and evaluation of the project indexes.

Our goal is to provide factual arguments to monitor projects and support decision-making, based on the knowledge about the status of the system being engineered, the progress of the project, and the increased reliability of the prediction.

B. Detailed Presentation of the Methodology Proposed

This section details the principles of the proposal. Section III-B1 defines a set of project performance indicators; Section III-B2 introduces how indicator performance indexes and weights are cooperatively defined and evaluated; Section III-B3 focuses on process performance indexes and their weights while Section III-B4 focuses on project performance indexes.

1) Definition of Indicators: Indicators have several roles, such as controlling and monitoring the performance of a project, analyzing options, detecting and mitigating risks, anticipating opportunities, and supporting decision-making [13]. In our proposal, the points of view of the manager and engineer are jointly considered into a definition of indicators. We extend the traditional project performance indicators (cost: I_c, duration: I_d, and resource: I_r) with two indicators (I_{in}: input criterion and I_{out}: output criterion) that are extracted from the international PM and SE references (ISO/IEC 15288 [36] and PMBoK [37]). To provide an overview of the project status, we give each indicator three values: 1) the planned value (PV); 2) the actual value (AV); and 3) the earned value (EV). This definition of multiple values for indicators is inspired from the EV method (EVM) technique, classically used for measuring project performance and progress in an objective manner [38]–[40]. Once this information on hand, the current status of the project can be compared with the planned progress [41].

At the beginning of a project, the PV of each indicator for each process should be given. After the work breakdown structure, all PVs should be attributed. During the realization of each process, the earned and AVs should be updated. Values are attributed by both project managers and systems engineers when they want to evaluate the progress of the project. Each process is characterized by these five indicators. They are presented here below.

a) Input criterion: This indicator I_{in} indicates the minimally acceptable inputs to perform the process. Its PV, AV, and EV are defined as

$v_{\text{in}}^{\text{pv}}$ = number of the inputs required by the process
$v_{\text{in}}^{\text{av}}$ = number of the inputs finished at this moment
$v_{\text{in}}^{\text{ev}}$ = number of the budgeted inputs performed.

For instance, the PMBoK Guide's "plan risk management" has five inputs: 1) "PM plan"; 2) "project charter"; 3) "enterprise environmental factors"; 4) "stakeholder register"; and 5) "organizational process assets." If at the moment when the indicator values should be calculated, the five inputs should be fulfilled but only the PM plan and stakeholder register are fulfilled and the number of the budgeted inputs performed is 3, the values then are

$$v_{\text{in}}^{\text{pv}} = 5, \quad v_{\text{in}}^{\text{av}} = 2, \quad v_{\text{in}}^{\text{ev}} = 3.$$

b) Process cost: Indicator I_c corresponds to the amount of money allocated to a process. It is used to evaluate if the process is over or under budget. Its PV, AV, and EV are defined as

v_c^{pv} = PV of the cost of this process
v_c^{av} = AV of the cost of this process
v_c^{ev} = budgeted cost of this process performed.

Suppose that we take a process to which \$20 000 have been allocated. If the cost spent until now is \$10 000 and the budgeted cost of the fulfilled work for the process is \$6000, then values are

$$v_c^{\text{pv}} = 20\,000, \quad v_c^{\text{av}} = 10\,000, \quad v_c^{\text{ev}} = 6000.$$

c) Process duration: Indicator I_d indicates the duration of a process. It is used to evaluate if the project is behind or ahead of schedule. Its PV, AV, and EV are defined as

v_d^{pv} = PV of the time required of this process
v_d^{av} = AV of the time spent on this process
v_d^{ev} = budgeted time of this process performed.

For instance, suppose that a process requires 800 work hours, the time spent is 400 h and the budgeted time to finish the work is 600 h. Then

$$v_d^{\text{pv}} = 800, \quad v_d^{\text{av}} = 400, \quad v_d^{\text{ev}} = 600.$$

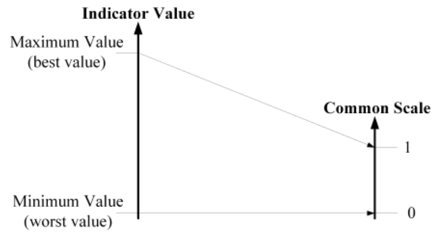

Fig. 3. Transferring indicators values to the same scale [0-1].

d) Process resource: Indicator I_r corresponds to the resources that could not be expressed in money, such as human resources. It is used to evaluate if project resource is over or under the company capacity. Its PV, AV, and EV are defined as

v_r^{pv} = PV of the resource required of this process

v_r^{av} = AV of the resource spent on this process

v_r^{ev} = budgeted resource of this process performed.

If we consider a process to which 22 workers have been allocated, to which resource assigned currently is 18 workers and the budgeted resource of the fulfilled work is 16 workers, then there are

$$v_r^{\mathrm{pv}} = 22, \quad v_r^{\mathrm{av}} = 18, \quad v_r^{\mathrm{ev}} = 16.$$

e) Output criterion: Indicator I_{out} indicates the minimally acceptable outputs to perform the next process. Its PV, AV, and EV are defined as

$v_{\mathrm{out}}^{\mathrm{pv}}$ = number of the outputs required of this process

$v_{\mathrm{out}}^{\mathrm{av}}$ = number of the outputs finished at this moment

$v_{\mathrm{out}}^{\mathrm{ev}}$ = number if the budgeted outputs performed.

For instance, the PMBoK Guide's "control communication" has five outputs: 1) "work performance information"; 2) "change requests"; 3) "PM plan updates"; 4) "project document updates"; and 5) "organizational process assets updates." If at current time, three outputs should be fulfilled but only work performance information and change requests are fulfilled and the number of the budgeted outputs performed is 2, then we have

$$v_{\mathrm{out}}^{\mathrm{pv}} = 3, \quad v_{\mathrm{out}}^{\mathrm{av}} = 2, \quad v_{\mathrm{out}}^{\mathrm{ev}} = 2.$$

In this section, a set of five-core indicators were defined. It should be noted that depending on project or company, stakeholders from PM and SE can define additional specific indicators.

2) Definition and Evaluation of Indicators:

a) Definition and evaluation of indicator values: Indicators values are obtained by consulting the project managers and systems engineers through interviews or using the Delphi method [42], [43]. Note that the different indicator value magnitudes may be very different. For example, if we consider a set of indicator values as

$$v_{en}^{\mathrm{pv}} = 2, \ v_c^{\mathrm{pv}} = 5000, \quad v_d^{\mathrm{pv}} = 2, \quad v_r^{\mathrm{pv}} = 6, \quad v_{\mathrm{out}}^{\mathrm{pv}} = 4.$$

It means that we only consider the cost impact on the process. To have a homogeneous equation, we must transfer the values of indicators to a space between 0 (worst) and 1 (best) as shown in Fig. 3.

b) Definition and evaluation of indicator indexes: We define two indicator performance indexes, indicator earned performance index (InEPI) and indicator actual performance index (InAPI), according to the EVM

InEPI $= v^{\mathrm{ev}}/v^{\mathrm{pv}}$ (better if greater than 1)

InAPI $= v_p^{\mathrm{ev}}/v_p^{\mathrm{av}}$ (better if greater than 1)

where the InEPI examines the performance of the indicator while the InAPI examines the efficiency of the completed work by evaluation of this indicator. Four possible cases can be identified.

If InEPI $\geq$ 1 and InAPI $\geq$ 1, it means that the indicator performance is great both in its completeness and the efficiency of the use content that this indicator represents.

If InEPI $\geq$ 1 and InAPI $<$ 1, it means that the indicator performance is great but the efficiency of the use content that this indicator represents is not efficiency because of longer duration, more resources, and lack of intermediate product or other reasons. In order to reveal the reasons, we need to analyze the PV, AV, and EV of the indicator with the project manager, systems engineers, and consultants.

If InEPI $<$ 1 and InAPI $\geq$ 1, it means that the indicator performance is not great but this indication is not very relevant. In order to deepen the diagnosis, we need to analyze the PV, AV, and EV of the indicator with the project manager, systems engineers, and consultants.

If InEPI $<$ 1 and InAPI $<$ 1, it means that the indicator performance is not great and the efficiency of the use content that this indicator represents is not efficiency. In order to reveal the reason, we need to analyze the PV, AV, and EV of the indicator with the project manager, systems engineers, and consultants. Then we can also adjust the project policy dynamically by increasing investment in the values of each indicator.

c) Definition and evaluation of indicator weights: Indicators can be used to evaluate the performance of an activity, a process, or a project. However, it is worth noting that the impact of indicators is different according to the stages of product life cycle. For instance, duration is less important at the end of a project. To deal with this situation, we propose to use AHP method to make project managers and systems engineers to combine qualitative and quantitative factors in the cases where they cannot give exact indicator weights directly. AHP helps decision makers find one decision that best suits their goal and their understanding of the problem [44]. It provides a comprehensive and rational framework for structuring a decision problem, for representing and quantifying its elements, for relating those elements to overall goals and for evaluating alternative solutions [45]. Here, it allows the integration of project managers and systems engineers' inputs by assigning indicator weights in a pairwise manner. By using AHP, we can change the impact of indicators on a project's assessment at each project milestone, by not only using indicator weights to evaluate project performance but also integrating inputs from project managers and systems engineers as well. In other words, we use the AHP method to consider the important impact that project managers' and systems engineers' experiences can have on project progress evaluation.

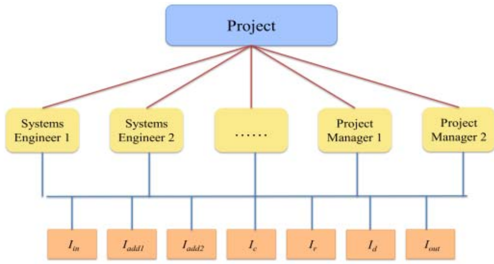

Fig. 4. AHP method applied to our proposal.

In the assessment framework given in Fig. 4, a project is represented as the goal and the expertise of several stakeholders from PM and SE is considered to evaluate project progress, thus providing a cooperative view. We give the weights of indicators with the AHP method. PM and SE stakeholders can have different weights of indicators according to their preferences.

The main steps of applying the AHP method are as follows.

1) Generate a pairwise comparison matrix for stakeholders based on their experiences and expertise.
2) Calculate the stakeholders' weights based on the matrix.
3) Generate a pairwise comparison matrix of indicators for each stakeholder.
4) Calculate the indicators' weights.

3) Definition and Evaluation of Process Indexes and Weights:

a) Definition and evaluation of process indexes: Stakeholders gave priorities to indicators to calculate their weights using the AHP method. According to the indicator performance indexes defined in Section III-B2b and the EVM method, we also define two process performance indexes to measure the progress of the process: 1) process earned performance index (PcEPI) and 2) process actual performance index (PcAPI)

1) $\text{PcEPI} = \sum_{i=1}^{n} W_i^{\text{AHP}} \text{InEPI}_i$ (better if greater than 1)
2) $\text{PcAPI} = \sum_{i=1}^{n} W_i^{\text{AHP}} \text{InAPI}_i$ (better if greater than 1)

where the InEPI_i and InAPI_i are the index performance values of the ith indicator of the process, and n is the number of indicators.

If a process has not started yet, $\text{PcEPI} = 1$ and $\text{PcAPI} = 1$.

If a process has started while $\text{PcEPI} \geq 1$ and $\text{PcAPI} \geq 1$, it means that the process runs well (completeness and efficiency).

If a process has started while $\text{PcEPI} \geq 1$ and $\text{PcAPI} < 1$, it means that the process has been finished on time but the work related to this process is not efficiency because of longer duration, more resources, or other reasons. In order to reveal the reason, we need to go deep into the indicator level and analyze their values and weights.

If a process has started while $\text{PcEPI} < 1$ and $\text{PcAPI} \geq 1$, it means that the process has not been finished on time, but the work related to this process is very efficiency. In order to reveal the reason, we need to go deep into the indicator level and analyze their values and weights.

If a process has started while $\text{PcEPI} < 1$ and $\text{PcAPI} < 1$, it means that the process does not run very well both in its completeness and efficiency. In order to deepen the diagnosis, we need to go deep into the indicator level and analyze their values and weights. Then stakeholders can adjust the project policy dynamically by increasing investment in some of the project indicators with the weights of those indicators.

We aggregate figures of indicators based on their weights. Thus, it is necessary to analyze the case when there are some indicator performance indexes in opposite directions. In this case, we can also conclude that the process performance indexes are greater than 1. We thus use average and variance of the indicator performance indexes defined as follows:

$\text{Average(InEPI)} = \text{InEPI}_a = (\sum_{i=1}^{n} \text{InEPI}_i)/n$ (better if greater than 1)

$\text{Average(InAPI)} = \text{InAPI}_a = (\sum_{i=1}^{n} \text{InAPI}_i)/n$ (better if greater than 1)

$\text{Variance(InEPI)} = \text{InEPI}_v = (\sum_{i=1}^{n} |\text{InEPI}_i - \text{InEPI}_a|^2)/n$ (best if equal to 0)

$\text{Variance(InAPI)} = \text{InAPI}_v = (\sum_{i=1}^{n} |\text{InAPI}_i - \text{InAPI}_a|^2)/n$ (best if equal to 0).

If InEPI_a and InAPI_a, are greater than 1, that means that from the overall view, the project progress is good at the indicator level. The values of InEPI_v and InAPI_v analyze the opposite directions of the indicator performance indexes; the smaller the values are, the better the evaluation results are.

b) Cooperative evaluation of the process weight: We could obtain the project performance indexes based on the process performance indexes. However, it is obvious that project's processes do not have the same importance. For example, the "transition process" probably has less importance than the "architecture design process." Their respective impact on decision-making is related to their relative importance. Thus, we allocate weights to processes according to their importance. Additionally, as projects increase in scale, it is necessary to distinguish the processes that must begin and finish on time, so we use the critical path method (CPM) [46]–[48] to find processes on the critical path of a project and assign different weights. The weight of a process is computed using CPM. This section introduces how to use CPM to obtain process weights. To use CPM, we need to initiate the processes related to a phase at the beginning of each phase. Then, with the process start time and duration, processes belonging to the critical path of this phase, which must start and finish on time, can be identified. Let W_i^{CPM} represent the weight of this process, meaning that it is the CPM weight value of the ith process of a project.

This implementation of CPM consists of an algorithm to schedule project activities on the basis of: 1) a list of processes; 2) the duration of each process; and 3) dependencies between processes. Here are the steps to calculate the weight values of the processes with CPM.

1) Calculate the earliest time of the ith process: ve_i.
2) Calculate the latest time that the ith process can be implemented vl_i.
3) Calculate the difference between them $vd_i = vl_i - ve_i$.
4) Calculate the value w_i^{CPM}: $w_i^{\text{CPM}} = 1 - [vd_i/(\text{Max}\{vd_i\} + 1)]$.
5) Normalize w_i^{CPM}.

We obtain the weight of a process; this value is related to the flexible time of a process. Processes belonging to the critical path have the greatest values because they must start and finish on time as they have no time flexibility. The processes that have the same time flexibility have the same weights. Processes having the same difference of duration have the same weights.

4) Definition and Evaluation of the Project Indexes: According to the EVM method, we define two additional project performance indexes: 1) project earned performance index (PjEPI) and 2) project actual performance index (PjAPI) for evaluating project progress at the project level

$\text{PjEPI} = \sum_{i=1}^{m} W_i^{\text{CPM}} \text{PcEPI}_i$ (better if greater than 1)

$\text{PjAPI} = \sum_{i=1}^{m} W_i^{\text{CPM}} \text{PcAPI}_i$ (better if greater than 1)

where PcEPI_i and PcAPI_i are the process performance values of the ith process of the project, and m is the number of processes. The PjEPI examines the completeness of the project while the PjAPI examines the efficiency of the completed work related to this project. Here, we have five possibilities of these project performance indexes.

If a project has not started yet, PjEPI $=1$ and PjAPI $=1$.

If a project has started while PjEPI ≥ 1 and PjAPI ≥ 1, it means that the whole project or at least the most important processes of this project run very well both in its completeness and efficiency at the project level.

If a project has started while PjEPI ≥ 1 and PjAPI < 1, it means that the project has been finished on time but the work has been done in this project was not efficiency because of longer duration, more resources or other reasons. In order to find the real reason, we need to go deep into the process level and indicator level and analyze their values and weights.

If a project has started while PjEPI < 1 and PjAPI ≥ 1, it means that the project has not been finished on time, but the work has been done in this project was very efficiency. In order to find the real reason, we need to go deep into the process level and indicator level and analyze their values and weights.

If a project has started while PjEPI < 1 and PjAPI < 1, it means that the project does not run very well both in its completeness and efficiency. In order to find the real reason, we need to go deep into the process level and indicator level and analyze their values and weights. Then stakeholders can adjust the project policy dynamically by increasing investment in some of the values and weights of some indicator and process.

As the definition of both project performance indexes, we aggregate figures of the process performance indexes based on the weights of the processes. It is necessary to analyze the case where process performance indexes are in opposite directions, but we can also conclude that the project performance indexes are greater than 1. So, considering this case, we use average and variance of the process performance indexes.

1) Average(PcEPI) $= \text{PcEPI}_a = (\sum_{i=1}^{m} \text{PcEPI}_i)/m$ (better if greater than 1).
2) Average(PcAPI) $= \text{PcAPI}_a = (\sum_{i=1}^{m} \text{PcAPI}_i)/m$ (better if greater than 1).
3) Variance(PcEPI) $= \text{PcEPI}_v = (\sum_{i=1}^{m} |\text{PcEPI}_i - \text{PcEPI}_a|^2)/n$ (best if equal to 0).
4) Variance(PcAPI) $= \text{PcAPI}_v = (\sum_{i=1}^{m} |\text{PcAPI}_i - \text{PcAPI}_a|^2)/n$ (best if equal to 0).

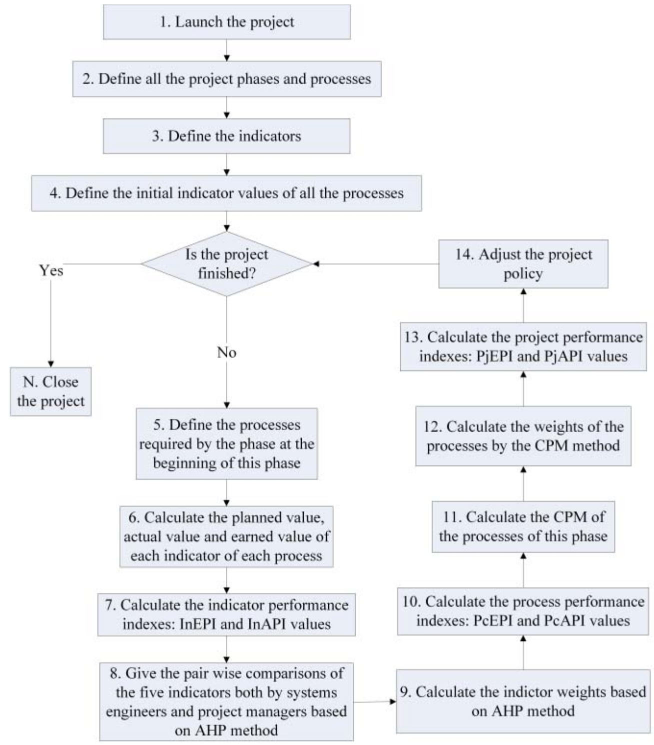

Fig. 5. Steps of the cooperative monitoring process method implementation.

PcEPI_a and PcAPI_a, greater than 1 means that from the overall view, the evaluation of project progress at the process level is good. The values of PcEPI_v and PcAPI_v analyze the opposite directions of the process performance indexes, the smaller the values are, the better the evaluation results are.

By using these performance indexes, we can evaluate the progress of the processes and also the progress of the project. Moreover, we can simulate the “right” indexes value by changing the indicators’ value, so that we can see the change of which one can raise different indexes values. Based on this simulation, we can forecast the expected outcome of a project by simulating the values of the project with the assumed values of the indexes.

C. Implementation of the Cooperative Monitoring Process

This section explains how the cooperative monitoring process is used during the whole life cycle of project, from the project definition till its closure.

It consists of 14 steps as shown in Fig. 5.

1) Launch a project.
2) Define the phases and processes of the project according to its stakeholders.
3) Define the indicators.
4) Define the initial indicator values of all the processes. We then use the proposed methodology at the beginning of each phase of the project until it is finished.
5) Define the processes required by the current phase.
6) Calculate the AV and EV of each indicator of each process.

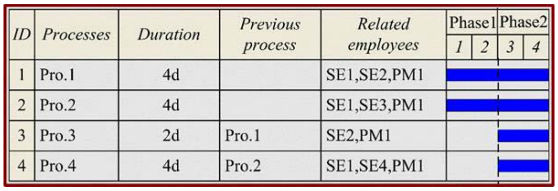

Fig. 6. Gantt chart for the example project.

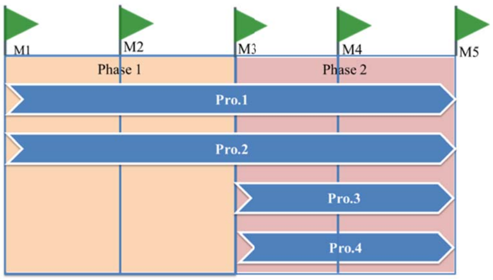

Fig. 7. Milestones of the example project.

7) Calculate the indicator performance indexes: InEPI and InAPI.
8) Give the pairwise comparisons of the five indicators' weights both by project managers and systems engineers according to the AHP method.
9) Calculate the weights of the indicators based on the AHP method.
10) Calculate the process performance indexes: PcEPI and PcAPI for all the processes.
11) Find the critical path of all processes, which means that processes must be started and finished on time in this phase based on the CPM method.
12) Calculate process weights based on the CPM method.
13) Calculate the project performance indexes: PjEPI and PjAPI.
14) Analyze the evaluation result and adjust the project policy based on the two project performance indexes.

IV. Illustrations of Key Stages of Cooperative Monitoring Process Method

In order to illustrate the key stages of the cooperative monitoring process implementation, let us consider a simple scholar project with two phases, four processes (Pro. 1–Pro. 4), four stakeholders from SE (SE1–SE4), and one stakeholder from project manager (PM1). Fig. 6 establishes the Gantt chart for this example.

A. Application of AHP Method

Let us calculate indicator weights. Without loss of generality, we only consider five core indicators for four processes (Pro.1–Pro.4). The project has two phases. We consider breaking it down into five milestones (M1–M5). M1 corresponds to the beginning of phase 1; M2 to the middle of phase 1; M3 to the end of phase 1; M4 to the middle of phase 2; and M5 to the end of the project as shown in Fig. 7.

At each milestone, each stakeholder who takes part in the phase establishes relative priorities among the indicators to

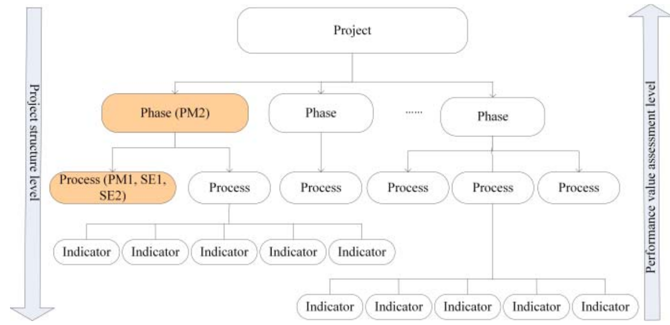

Fig. 8. Implementation of the AHP method.

calculate their weights. Let us use M3 to explain how the AHP method is implemented to generate the indicator weight of process Pro.1. Only the roles SE1, SE2, and PM1 are considered; however, it is worth noting that we need to analyze the positions of the three different roles. For example, according to the hierarchical company organization and the project size, a pairwise comparison matrix (A) of SE1, SE2, and PM1 can be given by the previous project managers (PM2), as shown in Fig. 8. In fact, the relative weights of SE_i and PM_i could be generated on the basis of other features of the project.

At M3, the matrix ($A = (a_{ij})_{3\times 3}$) for SE1, SE2, and PM1 can be given by PM2 to calculate the weights and three other pairwise comparison matrices (SE_1, SE_2, and PM_1) can be given by the three related roles SE1, SE2, and PM1 to calculate the indicator weights. For instance, the matrix for SE1, SE2, and PM1 is shown below. In this matrix, we can see that PM2 considers that the SE1 is twice important than PM1

$$A = \begin{pmatrix} 1 & 1 & 1/2 \\ 1 & 1 & 1/2 \\ 2 & 2 & 1 \end{pmatrix}.$$

This matrix shows that SE1 is as important as SE2 and half as important as PM1. Based on matrix A, a weight vector $\hat{w} = (\widehat{w_1}, \widehat{w_2}, \widehat{w_3})^T$ can be generated as follows:

$$\hat{W} = \left(\frac{1}{4}, \frac{1}{4}, \frac{1}{2}\right)^T.$$

The next three matrixes, each for the five indicators, are given by SE1, SE2, and PM1, respectively

$$SE_1 = \begin{pmatrix} 1 & 1/2 & 5 & 4 & 6 \\ 2 & 1 & 3 & 2 & 3 \\ 1/5 & 2/5 & 1 & 1 & 6/5 \\ 1/4 & 1/2 & 1 & 1 & 2 \\ 1/6 & 1/3 & 5/6 & 2/3 & 1 \end{pmatrix}.$$

In this matrix, for example, we can see that SE1 considers the "input criterion" is twice more important for him than the "cost" criteria. Its maximum eigenvalue is $\lambda_{\max SE_1} = 5.2090$ and the consistency Ratio (CR) is $CR(SE_1) = 0.0466$ less than 0.1, so the judgements by SE1 can be regarded consistent. We then get the weights of the five indicators as judged by SE1: $w_{SE_1} = (0.3681, 0.3484, 0.0849, 0.1205, 0.0781)^T$. The other

TABLE I
INDICATOR WEIGHTS FOR PROCESS "PRO.1"

	1/4(SE1)	1/4(SE2)	1/2(PM1)	Indicator weight
Input criterion	0.3681	0.4386	0.4381	0.4207
Cost	0.3484	0.1462	0.1049	0.1761
Duration	0.0849	0.2156	0.1460	0.1481
Resource	0.1205	0.1096	0.0918	0.1034
Output criterion	0.0781	0.0899	0.2191	0.1515

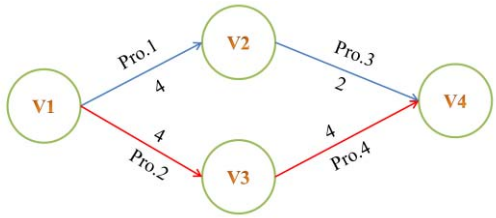

Fig. 9. Network planning.

two matrixes are as follows:

$$\mathrm{SE}_2 = \begin{pmatrix} 1 & 3 & 2 & 4 & 5 \\ 1/3 & 1 & 2/3 & 4/3 & 5/3 \\ 1/2 & 3/2 & 1 & 11/6 & 5/2 \\ 1/4 & 3/4 & 1/2 & 1 & 5/4 \\ 1/5 & 3/5 & 2/5 & 9/10 & 1 \end{pmatrix}$$

$$\mathrm{PM}_1 = \begin{pmatrix} 1 & 4 & 3 & 5 & 2 \\ 1/4 & 1 & 3/4 & 1 & 1/2 \\ 1/3 & 4/3 & 1 & 5/3 & 2/3 \\ 1/5 & 1 & 3/5 & 1 & 2/5 \\ 1/2 & 2 & 3/2 & 5/2 & 1 \end{pmatrix}.$$

Similarly, the maximum eigenvalue for SE2 is $\lambda_{\mathrm{maxSE}_2} = 5.0083$ and $\mathrm{CR}(\mathrm{SE}_2) = 0.0019$; the maximum eigenvalue for PM1 is $\lambda_{\mathrm{MAXPM1}} = 5.0060$ and $\mathrm{CR}(\mathrm{PM}_1) = 0.013$. We get $w_{\mathrm{SE}_2} = (0.4386, 0.1462, 0.2156, 0.1096, 0.0899)^T$ and $w_{\mathrm{PM}_1} = (0.4381, 0.1049, 0.1460, 0.0918, 0.2191)^T$. The indicator weights for "Pro.1" are summarized in Table I.

Let us take the toy project to calculate the process weight with the CPM method. The PERT chart is given by Fig. 9. V1 correspond to the start of the project, processes "Pro.1" and "Pro.2" do not have any preceding process, processes "Pro.1" and "Pro.2" each takes four days in duration. Process "Pro.3" is preceded by "Pro.1" and lasts four days. Process "Pro.4" is preceded by "Pro.2" and lasts four days.

According to the CPM steps previously explained, Pro.2 and Pro.4 are critical processes with these values

$$\begin{aligned} &ve(\text{Pro.1}) = 0,\ \ vl(\text{Pro.1}) = 2,\ \ vd(\text{Pro.1}) = 2 \\ &ve(\text{Pro.2}) = 0,\ \ vl(\text{Pro.2}) = 0,\ \ vd(\text{Pro.2}) = 0 \\ &ve(\text{Pro.3}) = 4,\ \ vl(\text{Pro.3}) = 6,\ \ vd(\text{Pro.3}) = 2 \\ &ve(\text{Pro.4}) = 4,\ \ vl(\text{Pro.4}) = 4,\ \ vd(\text{Pro.4}) = 0. \end{aligned}$$

After that calculus, we obtain the four weight values of processes

$$\text{Weight}(\text{Pro.1},\ \text{Pro.2},\ \text{Pro.3},\ \text{Pro.4}) = \left(\frac{1}{8}, \frac{3}{8}, \frac{1}{8}, \frac{3}{8}\right).$$

TABLE II
ORIGINAL INDICATOR VALUES OF PROCESS PRO.1

	Input criterion	Cost	Duration	Resource	Output criterion
Plan values	0	5,000	2d	6 employees	4
Actual value	0	4,000	5d	7 employees	4
Earned value	0	3,000	3d	10 employees	2
Indicator weight	0.4207	0.1761	0.1481	0.1034	0.1515

TABLE III
ADAPTIVE INDICATOR VALUES FOR PROCESS PRO.1

	Input criterion	Cost	Duration	Resource	Output criterion
Plan values	0	1	0.4	0.6	1
Actual value	0	0.8	1	0.7	1
Earned value	0	0.6	0.6	1	0.5
Indicator weight	0.4207	0.1761	0.1481	0.1034	0.1515

TABLE IV
INDICATOR PERFORMANCE INDEXES FOR PROCESS PRO.1

Indicator	Input criterion	Cost	Duration	Resource	Output criterion
InEPIi	1	0.6	1.33	1.67	0.5
InAPIi	1	0.75	0.6	1.43	0.5

B. Application of EVM Method

Let us take process Pro.1 from the previous example to explain how to calculate the two process indexes. At milestone M3, the three values of the five indicators appear in Table II.

To have a homogeneous equation, we transfer the values of each indicator to a common space, with values from 0 (worst) to 1 (best), so that adding the value of cost and the value of duration has a meaning. In this example, the change of scale results in Table III.

C. Evaluation of the Scholar Project

According to the previous definitions of indicator, process, and project performance indexes, we get the values of five indicator performance indexes as in Table IV.

According to the five indicator performance indexes, we can note that the evaluation results of these indicators are not so good except indicator *resource*. Then we can calculate that PcEPI (Pro.1) = 0.997 and PcAPI (Pro.1) = 0.865. Based on these two indexes, we note that process Pro.1 does not progress well. We can obtain the $\mathrm{InEPI}_a = 1.02$ and $\mathrm{InEPI}_v = 0.9658$. From the average of the InEPIs, we can see that the InEPI_a is greater than 1 that means these indicator performances are good. However, if we look at the InEPI_v, it is equal to 0.9658 and it is not good. According to this analysis result, it can be concluded that the InEPIs

TABLE V
COMPARISON OF TWO PROJECT INDEX POSSIBILITIES

	Pro.1	Pro.2	Pro.3	Pro.4
Weight	1/8	3/8	1/8	3/8
PjEPI value 1	1	1	2	0.4
PjEPI value 2	1	1	2	2

are good overall while there are some InEPIs are in opposite directions. This analysis result means that there are some indicator earned performances are greater than 1 and the others are less than 1. If we look at Table IV, it is obvious that the "duration" and "resource" earned performance indexes are greater than 1 whereas the "cost" and "output criterion" earned performance indexes are much less than 1. Similarly, we can also obtain the $\text{InAPI}_a = 0.856$ and $\text{InAPI}_v = 0.5536$. it can be concluded that the InAPIs are not good and there are some InAPIs are in opposite directions. This analysis result can be validated by the indexes values in Table IV. Considering the project performance indexes, the process weight is important for both of them; let us take a simple example to explain. We define two possibilities for all PcAPI values for the four processes (Pro.1–Pro.4) as shown in Table V.

As shown in Table V, process Pro.3 has a high-performance evaluation for the first possibility of indexes; however, the project progress evaluation is not very good because process Pro.4 has a higher weight. Thus, by comparing the two project performance index possibilities, we can conclude that the process weight is very important in evaluating the progress of the project.

Using the four performance indexes, we can evaluate the progress of the processes and also the progress of the project. Moreover, we can simulate the "right" index value by changing the indicators' value, so that we can see the change of which one can raise different performance indexes values. Based on this simulation, we can forecast the expected outcome of a project by simulating the values of the project with the assumed values of the indexes.

V. CASE STUDY

This section explains how to implement the methodology on a student's project.

A. Introduction to the Project

We selected the work of a team of students from the University of Toulouse, which took part in the RobAFIS Competition (held in 2015), as a case study [49]. This competition consisted of a comparative assessment between LEGO robots on a given mission [49]. Students first needed to identify their resources, budget, deadlines, and all other important information required to deliver the perfect system on time. Then, they had to organize, divide and plan the project before beginning the technical aspects that engineers generally handle (system analysis, conception, integration, tests, etc.). Each team had around four months to carry out its project. The development documents included the SE processes they used during the project and all the information that we need to calculate the project progress.

B. Application of Our Proposal to the Case Study

This section explains the key steps of the use of the cooperative monitoring process method to monitor the project progress of our case study. First, we discuss the indicators used in this case study. Considering that companies can use their own project and product indicators, we use two indicators (duration and resource) that we defined in Section III-B1. We evaluate the indicator, process and project performance indexes at one milestone based on the indicators in details and provide only the evaluation results for the other milestone. We validate the evaluation results using the risk analysis report that has been described in the project report to see if the evaluation is accurate and if the proposed methodology can actually monitor project progress. We explain the application of the cooperative monitoring process method in details and then draw a conclusion.

1) Definitions of the Indicators: To calculate more easily, we selected some common indicators mentioned in their development documents.

1) *Duration (in Hours or Weeks):* This indicator allows us to evaluate the time performance.
2) *Resources:* For calculating the project resources, we chose the number of people working on a process because it is much easier to identify and calculate.

We define two indicator performance indexes, two process performance indexes, and two project performance indexes (as previously discussed in Sections III-B2–III-B4) to aggregate the lowest level project evaluation result (indicator level) into the middle project evaluation result (process level) and the highest project evaluation result (project level) as shown in Fig. 1. By using these indexes, we can analyze each project progress in detail. In general, if an index is greater than one, it does not necessarily indicate a good situation for the project. For example, it could mean that a delay occurred, or that more people were finally needed to complete the process. To precisely follow the progress of the INSA project, we use the students' milestone dates available in the project reports as our evaluation milestones.

2) Definition of the Project Phases and Standardization of Project Processes: The first step of this implementation approach is to divide the projects into key phases. Based on documentation relative to coordination between project managers and systems engineers, we also attempt to identify the standardized processes in their development documents. To analyze the project correctly, we contacted the team members who were able to provide us with the information regarding the duration and resources. Fig. 10 shows the overall division of the student project into phases and processes.

3) Implementation of Cooperative Monitoring Process on the Case Study: Once the project phases and processes are defined, we can illustrate how to use our cooperative monitoring process in this case. In this section, the application of our proposal will be explained in detail. We will evaluate

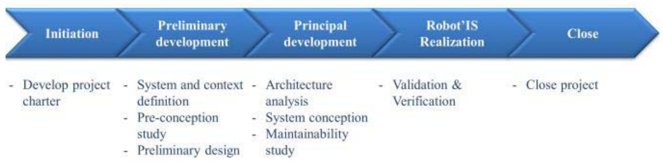

Fig. 10. Project phases and processes of the student project.

the project progress at one milestone. Based on the evaluation results, we will show that our cooperative project process works well. Here, we have chosen the end of the "system and context definition" process as the milestone.

a) Application of the AHP method to the case study: According to our proposed cooperative monitoring process, we use the AHP method to evaluate the indicator weights given by all the project roles. There are eight group members: one project manager (PM), two quality assurers (QA1 and QA2), two architects (AR1 and AR2), and three systems engineers (SE1–SE3). A pairwise comparison matrix ($A = a_{ij_{8\times 8}}$) of PM, QA1, QA2, AR1, AR2, and SE1–SE3 is given by the project guider (the teacher lead) to calculate their weights on the evaluation. This matrix is shown as

$$A = \begin{pmatrix} 1 & 2 & 2 & 3/2 & 3/2 & 2 & 2 & 2 \\ 1/2 & 1 & 1 & 2/3 & 2/3 & 1 & 1 & 1 \\ 1/2 & 1 & 1 & 2/3 & 2/3 & 1 & 1 & 1 \\ 2/3 & 3/2 & 3/2 & 1 & 1 & 3/2 & 3/2 & 3/2 \\ 2/3 & 3/2 & 3/2 & 1 & 1 & 3/2 & 3/2 & 3/2 \\ 1/2 & 1 & 1 & 2/3 & 2/3 & 1 & 1 & 1 \\ 1/2 & 1 & 1 & 2/3 & 2/3 & 1 & 1 & 1 \\ 1/2 & 1 & 1 & 2/3 & 2/3 & 1 & 1 & 1 \end{pmatrix}.$$

The maximum eigenvalue can be calculated as $\lambda_{\max A} = 8.0022$. We obtain $\mathrm{CI}(A) = 3.14.\mathrm{e} - 4$ and $\mathrm{CR}(A) = 2.23\mathrm{e} - 4$ as less than 0.1. So based on matrix A, we can have the weight vector for the eight project roles $\widehat{w_A} = (\widehat{w_1}, \widehat{w_2}, \widehat{w_3}, \widehat{w_4}, \widehat{w_5}, \widehat{w_6}, \widehat{w_7}, \widehat{w_8},)^T$ as follows:

$$\hat{w} = \left(\frac{1}{5}, \frac{1}{10}, \frac{1}{10}, \frac{3}{20}, \frac{3}{20}, \frac{1}{10}, \frac{1}{10}, \frac{1}{10}\right)^T.$$

For all the eight roles in this project, at the end of the system and context definition process, they give the eight comparison matrices as follows:

$$P = \begin{pmatrix} 1 & 2 \\ 1/2 & 1 \end{pmatrix} \; \mathrm{QA1} = \begin{pmatrix} 1 & 3/2 \\ 11/15 & 1 \end{pmatrix}$$
$$\mathrm{QA2} = \begin{pmatrix} 1 & 2 \\ 8/15 & 1 \end{pmatrix} \; \mathrm{AR1} = \begin{pmatrix} 1 & 3/2 \\ 2/3 & 1 \end{pmatrix}$$
$$\mathrm{AR2} = \begin{pmatrix} 1 & 1/2 \\ 2 & 1 \end{pmatrix} \; \mathrm{SE1} = \begin{pmatrix} 1 & 1/2 \\ 2 & 1 \end{pmatrix}$$
$$\mathrm{SE2} = \begin{pmatrix} 1 & 1 \\ 1 & 1 \end{pmatrix} \; \mathrm{SE3} = \begin{pmatrix} 1 & 1 \\ 1 & 1 \end{pmatrix}.$$

The normalized vector, maximum eigenvalue λ, CI, and CR of all the eight matrixes are as shown in Table VI.

By calculating the CR of all the eight matrixes, we can conclude that all of them pass the consistency check. We can therefore have the indicator weights

$$w_{\text{duration}} = 0.5255 \quad w_{\text{resource}} = 0.4745.$$

TABLE VI
VECTOR, λ, CI, CR OF ALL EIGHT MATRICES

k	P	QA1	QA2	AR1	AR2	SE1	SE2	SE3
w_{k1}	2/3	0.6	0.5885	0.6	1/3	1/3	0.5	0.5
w_{k2}	1/3	0.4	0.4115	0.4	2/3	2/3	0.5	0.5
λ_k	2	2	2.0488	2	2	2	2	2
CI_k	0	0	0.0488	0	0	0	0	0
RIk	0	0	0	0	0	0	0	0

TABLE VII
CASE STUDY PROCESS INFORMATION

Process name	Process code	Duration (in days)	Previous process	Related employees
Develop project charter	A	10	0	4
System and context definition	B	6	A	5
Pre-conception study	C	5	B	4
Preliminary design	D	4	B	8
Architecture analysis	E	4	B	6
System conception	F	4	C, D, E	8
Maintainability study	G	3	F	3
Validation & Verification	H	8	G	8
Close project	I	1	H	4

TABLE VIII
ORIGINAL INDICATOR VALUES OF THE SYSTEM AND CONTEXT DEFINITION PROCESS

	Planned value	Actual value	Earned value
Duration	6	6	6
Resource	5	8	7.5

b) Application of CPM method: To calculate the process weights, we must first outline the project network planning. At the beginning of this project, the planned time for each process as shown in Table VII.

Based on the CPM steps that we explained previously, the $A, B, C, F, G, H,$ and I processes are critical processes. After calculating the values according to the steps presented in Section III-C, we can get the nine weight values of the processes as follows:

$$\mathrm{Weight}(A, B, C, D, E, F, G, H, I) = \left(\frac{1}{8}, \frac{1}{8}, \frac{1}{8}, \frac{1}{16}, \frac{1}{16}, \frac{1}{8}, \frac{1}{8}, \frac{1}{8}, \frac{1}{8}\right).$$

c) Application of the EVM method: As stated in Section V-B3, the milestone we selected was the end of the system and context definition process, which we defined as "*B*" process in Table VII. All three values from both indicators (duration and resource) are given in Table VIII.

TABLE IX
ADAPTIVE INDICATOR VALUES OF THE SYSTEM AND CONTEXT DEFINITION PROCESS

	Planned value	Actual value	Earned value
Duration	1	1	1
Resource	0.625	1	0.9735

TABLE X
PROCESS PERFORMANCE INDEXES OF THE CASE STUDY

	A	B	C	D	E	F	G	H	I
PcEPI	1	1.24	1.06	1.07	1.09	0.93	1.47	1.06	1
PcAPI	1	0.97	0.94	0.92	0.93	1.05	1.09	0.89	1

To have a homogeneous equation, we transfer the values of each indicator to a common space. In this example, the change of scale results in Table IX.

According to the definitions of indicator performance indexes, we can get $\text{InEPI}_d = 1$, $\text{InAPI}_d = 1$, $\text{InEPI}_r = 1.5$, and $\text{InAPI}_r = 0.9375$. Then, we thus can obtain the PcEPI (B) = 1.24 and the PcAPI (B) = 0.97. Based on the two indexes, we can conclude that process B can be finished on time or a little in advance because PcEPI is greater than 1. But if we look at the index PcAPI, we see that it is less than 1, which means that the work done thus far is not effective. According to their report, we find that the indexes work very well because they completed the work on time but needed three additional people to finish. If we analyze the index at indicator performance level in Table X, we can see that the *resource* indicator performance indexes are not good. In the project report, we found that they used more resources (three additional people) to finish the process on time. If we want to look deep into the possibility of the indicator performance indexes in opposite directions, we also can obtain the $\text{InEPI}_a = 1.25$, $\text{InAPI}_a = 0.97$, $\text{InEPI}_v = 0.125$, and $\text{InAPI}_v = 0.0019$. From the average of indicator performance indexes, we also can see that both indicator performance indexes are good overall, but if we see the variance of the indicator performance indexes, it can be concluded that both indicator performance indexes are in opposite directions.

At this moment, the project performance indexes PjEPI = 1.105 and PjAPI = 0.978. From the project performance indexes, we can see that the project can be finished on time but they will need more people or to replan the resources. If we want to look deep into the possibility of the process performance indexes in opposite directions, we can obtain the $\text{PcEPI}_a = 1.1$ and $\text{PcEPI}_v = 0.2$. According to this analysis result, it can be concluded that the PcEPIs are good overall while there are some PcEPIs are in opposite directions. This analysis result means that there are some process earned performances are greater than 1.1 and the others are less than 1.1. If we look at Table X, it is obvious that the "B" and "G" PcEPIs are greater than 1.1 while the rest PcEPIs are much less than 1.1. Similarly, we can also obtain the $\text{PcAPI}_a = 0.977$ and $\text{PcAPI}_v = 0.03$. it can be concluded that the PcAPIs are not good and there are some PcAPIs are in opposite directions. This analysis result can be validated by the indexes values in Table X. When looking at their report, we found that the same problem occurred during their project. We will analyze all the project processes according to our indicators and give the overall analysis in the next section.

C. Summary of the Case Study

As a reminder, the indicators considered here are: the duration (in days) and the human resources committed (in number of individuals). Following the detailed discussion of the case study in Section V-B3, in this section, we provide a more general analysis of the case study and explain what the indexes mean. If the first PcEPI index of a process is greater than 1, it means that the planning of the different characteristics of the process is good and the project is advancing very well. If the second PcAPI index of a process is greater than 1, it means that the work that has been done so far is effective. Now, we are going to study each process in their project based on the indexes.

1) Develop Project Charter: We can conclude that both indexes are equal to than 1. This shows that the team successfully planned this process and the first "initialization" phase, but they did not sufficiently take risk analysis into consideration during their work. They should have been more careful because this initialization phase could have a major impact on project execution.

2) System and Context Definition: As we analyzed in Section V-B3, the system and context definition process indexes are greater than 1 which means that this process has been finished on time or a little bit in advance, but more people were required to achieve this process. This problem resulted in the indexes of the following processes being less than 1. This is because there were insufficient resources to complete the process on time.

3) Preconception Study, Preliminary Design, and Architecture Analysis: As we predicted in the system and context definition process, all the values of the PcEPI indexes of these three processes are greater than 1 but PcAPI are less than 1 as the systems and context definition process because the team planned too short a duration for these processes according to the fixed resources.

4) System Conception: As a result of the analysis of the processes above, we can see that the team was not able to work effectively during this process.

5) Maintainability Study: The team successfully carried out this process because they added two more people to finish it. It is consistent with the indexes' values.

6) Verification and Validation: Verification and validation is crucial for being as prepared as possible for the project presentation. The PcEPI is greater than 1 because the project team can present their work on time. However, the PcAPI is less than 1, this may explain why a mistake was made on the day of presentation because their work is not effective.

7) Project Finalization: As we mentioned previously, the principal constraint the team had set was "the robot is ready on time and the reports submitted on time." The study of the indexes highlights this fact. Indeed, they are all equal to 1 for this and other phases. It shows that the team took all the necessary precautions to maintain absolute control in achieving this phase.

As we analyzed above, the indicator, process and project performance indexes can be used to monitor project performance. Our analysis results are consistent with the actual project progress. Moreover, the indicator, process and project performance indexes reveal the same problem faced by the project team as recorded in the project report. This case study serves to show that our proposed method can be applied to predict project risks and explain why there are problems and how to deal with them to reduce their negative impact on project advancement.

This case study also demonstrates the relevance of adopting a cooperative approach in decision making during engineering projects, involving all kinds of stakeholders. Indeed, it offers several interests. It extends the decision team by involving engineers to ensure that the decision is seen as less arbitrary, thus avoiding the project leader to deal with conflict resolution afterwards, which usually takes between 30% and 40% of his or her time [50].

VI. Conclusion

In this paper, the authors proposed a cooperative monitoring process which aims to help project managers to evaluate the project progress relying on an integrated view of different stakeholders. Three different levels of project performance indexes are provided in this process, which offer different views of project progress for different roles or stakeholders. It outlines an approach to aggregate project progress evaluations from the lowest level (indicator level) up to the highest level (project level). It also aggregates project performance indicators into several indexes. The analysis of the successive values of the indexes can help identifying the tendency of project progress, detecting, and anticipating project deviations. The methodology thus defines a cooperative monitoring process for the whole project. This process can be used at any time, during any phase, over the entire project life cycle. This paper explained the methodology and illustrated how to implement it using an example. A case study from a student competition was used to demonstrate the interests of the methodology for project monitoring.

The proposed methodology offers several advantages. It offers a specific view of the project progress through the PM and the SE prisms. It also allows the different stakeholders to define additional indicators beyond the ones proposed; a detailed analysis of the indexes allows predicting project progress and detecting risks. The indicators, process and project performance indexes calculus, integrating both project managers' and systems engineers' experiences, lead to a more reliable and rational decision making, more in line management or technical objectives. Decisions are based on less subjective and more traceable arguments. The cooperation between project managers and systems engineers also minimizes project risk by integrating stakeholders' experiences. Moreover, weights attribution can be improved and adjusted from one project to another, considering the results of previous projects. Last but not least, extending decisions to a team involves stakeholders, improves their motivation and makes the decision perceived as less arbitrary. Based on these results, research could be further expanded toward several directions. For instance, a tool offering a visual dashboard for the detection and analysis of objective discrepancies would be useful to support the methodology; it could also include the use of capitalized knowledge.

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