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RESEARCH ARTICLE

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# Lessons learned from developing and implementing refinery production scheduling technologies



**Abstract** An increasing number of novel and highly specialized computer-aided decision-making technologies for short-term production scheduling in oil refineries has emerged and evolved over the past two decades, thereby encouraging refiners to permanently rethink the way the refining business is operated and managed. In this report, we discuss the key lessons learned from one of the pioneering, yet daring, enterprise-wide programs entirely implemented in an energy company devoted to developing and implementing an advanced refinery production scheduling (RPS) technology, i.e., the RPS system of Petrobras. Apart from mathematical and information technology issues, the long-term sustainability of a successful RPS project is, we argue, the outcome of a virtuous cycle grounded on permanent actions devoted to improving technical education inside the organization, reinspecting organizational cultures and operational paradigms, and developing working processes.

**Keywords** automation, decision making, oil refinery, optimization, production scheduling

## 1 Introduction

Right after the successful launch of operations research (OR) in the inventive military arena of World War II, the oil industry inaugurated the industrial use of OR techniques (Symonds, 1955) and since then has played a forerunner role in driving the OR-based industrial automation agenda forward (Table 1) (e.g., Bonner and Moore, 1979; Cutler and Ramaker, 1979; Lee et al., 1996; Steinschorn and Hofferl, 1997; Magalhães et al., 1998; Pinto et al., 2000; Moro, 2003; Magalhães, 2004; Liporace et al., 2009; Feital et al., 2013; Mendoza et al., 2013).

However, despite the astonishing progress in refinery automation over the past half-century, refinery production scheduling (RPS) remains, not by accident, an open question. In didactic terms, RPS can be considered the "crystal ball" of the process engineer because it should provide plant operation foreseeability in an integrated manner. RPS serves as the bridge between production planning and execution (Fig. 1) by determining optimal operational decisions with respect to (a) resource selection and sequencing over time (start and end times for tasks), (b) operation modes and duration or campaign length, and (c) flow rates (e.g., feed or component flow rates for blending operations (the pooling problem)). Given that RPS is concerned with operational decisions, it has straightforward implications for achieving profitable and, most importantly, safe operation in a business in which humans and the environment are exposed to severe hazards. RPS now represents the refining core business for high-performing oil refineries (Joly, 2012).

Several energy companies have invested in developing their own applications since the 1990s mainly because of this development (e.g., Magalhães et al., 1998; Rigby et al., 1995; Steinschorn and Hofferl, 1997). The following are the main motivations that have promoted the in-house development of advanced RPS applications.

- Good system integration with other industrial automation applications and corporate systems;
- Modeling customization possibilities for meeting the specificities of the refining business;
- RPS expertise understood as a strategic value for the organization;
- Technological independence from the commercial software market; and

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**Table 1** Business layers and the corresponding opportunities, popular solution approaches, key hallmarks, and current trends in refinery optimization[a)]

| Layer | Opportunities (USD/Bbl) | Solution approaches | Strengths | Weaknesses | Current trends Increasing adoption of |
|---|---|---|---|---|---|
| Production planning | 1.00–2.00 | L<br>NL<br>DC | ↑Robustness<br>↑Accuracy<br>↑Integration | ↓Accuracy<br>↓Robustness<br>↑CPU cost | Nonlinear and multi-period models (integration with scheduling), planning under uncertainty |
| Production scheduling | 0.15–1.00 | EBS<br>DC<br>HB | ↓CPU cost<br>↑Solution quality<br>↓CPU cost | ↓Solution quality<br>↑CPU cost<br>↓Flexibility | Petroleomics, automatic rescheduling (integration with online applications toward smart manufacture), integrated plant optimization, hybrid solution approaches |
| Real-time optimization | 0.10–0.50 | L<br>NL<br>DC | ↑Robustness<br>↑Accuracy<br>↑Integration | ↓Accuracy<br>↓Robustness<br>↑CPU cost | Better analytical technologies for feed characterization, good phenomenological models for parameter estimation, good and time-efficient identification procedures, expansion toward nonlinear and hybrid (discrete-continuous) systems |

a)Typical opportunities to be captured by developing or implementing refinery optimization (US dollars per crude oil barrel, 1 Bbl = 159 L) are based on our experience and best knowledge and may depend on intrinsic (e.g., refinery complexity) and extrinsic factors from the refinery standpoint (e.g., supply chain management reliability). DC: Discrete-continuous optimization (e.g., mixed-integer programming); EBS: Event-based simulation; HB: Heuristic-based optimization; L: Linear optimization; NL: Nonlinear optimization

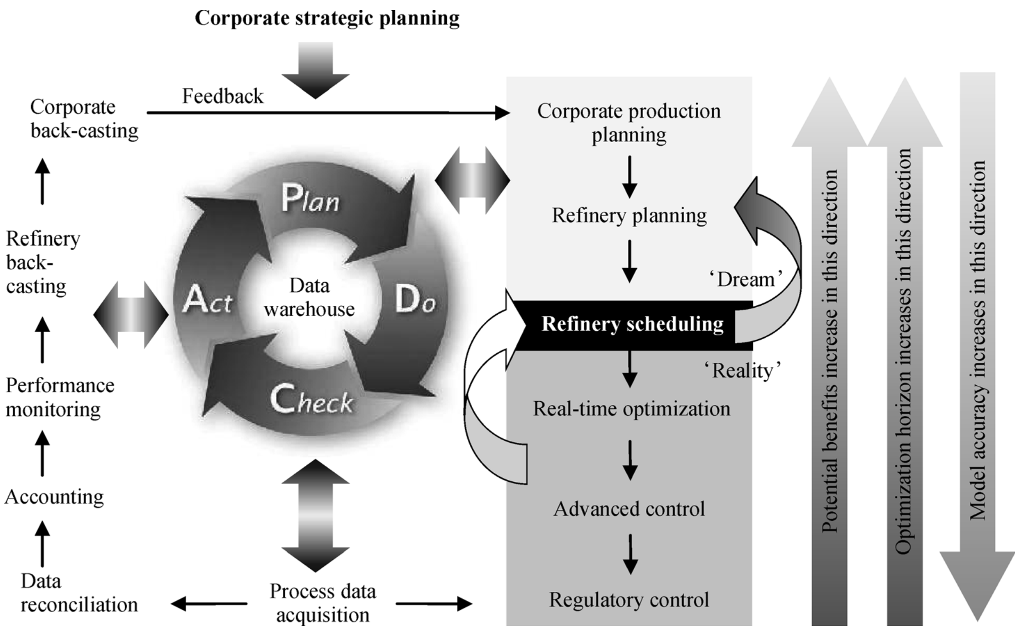



**Fig. 1** A real-world hierarchical decision-making framework for refinery automation (Joly, 2012)

• The actual possibility of going beyond what has been commercially attempted in terms of solution approaches (Agrawal and Balasubramanian, 2006).

The fourth industrial revolution, which is currently in its preludial stage, irrefutably invites us to assess what we have learned so far regarding developing and implementing RPS technologies in this context. In this article, we discuss the major lessons learned from one of the pioneering enterprise-wide programs devoted to developing and implementing advanced scheduling technologies for short-term production in the oil industry, i.e., the refinery scheduling system (BR-SIPP®) of Petrobras (Magalhães et al., 1998). The objectives of this study are as follows:

(a) To revisit and share two decades of industrial experience related to the in-house development and implementation of BR-SIPP;

(b) To discuss the potential factors (and the causality relationships among them) that may cause failure of the RPS project; and

(c) To present conclusions and general recommendations to colleagues who are tasked with developing, implementing, and/or maintaining advanced RPS solutions in industrial settings.

This article is organized as follows: Focusing on items (a) and (b), Section 2 presents an in-depth view of the main lessons learned (from project conception up to its operational plenitude). Item (c) is addressed in Section 3, which concludes the paper by summarizing the key insights into our experience and practice in RPS.

## 2 Lessons learned

### 2.1 Know the prerequisites of an RPS project

An RPS project involves two major work fronts, namely, initial implementation and maintenance over time. A third work front, i.e., technology development, may exist in companies that opt for technological independence from the industrial automation software market. The prerequisites for an acquired or self-developed RPS project startup are as follows:

I. **Refinery data organization and structuration**. This prerequisite is crucial because a large amount of operational and nonoperational data is required to run the RPS application. These data define the initial conditions of the model for the new run (e.g., starting inventories in tanks and pipelines and the corresponding qualities) and its configuration parameters (e.g., purchase and sale prices, crude oil yields, product specification limits, and operational bounds). Ideally, this large data set should be organized and stored in corporate systems and databases from which it can be efficiently and reliably fed into the RPS system. Manual data entry into the RPS tool is not a practical option. If the refinery's data organization and structuration are not complete, it may become the longest and most expensive step of the RPS project. This Herculean task often requires and opens many opportunities for the reassessment of working processes within the organization. For this reason, the highest leadership levels should be wholly committed to the RPS project. Otherwise, private initiatives at the technical or operational level will rest in the field of good intentions.

II. **Integrative working processes**. Harmonic, well-designed working processes are mandatory to supporting the RPS. First, well-defined interfaces and responsibilities among actors inside and outside the refinery should be ensured to avoid redundancy or gaps in the information flow to (i.e., the input data required to run the RPS application) and from (i.e., the optimal production schedule to be operationalized) the scheduling layer. Second, phone calls and customized Excel-like spreadsheets should be replaced by standardized and integrated information systems as much as possible to ensure data reliability (e.g., by eliminating errors from manual data input), information traceability (e.g., by ensuring rapid identification of the origin of problematic events), and individual-specific dependency elimination (i.e., "irreplaceable" people). Such actions are devoted to improving the quality of the critical analysis related to the RPS performance and hence to ensuring the continuous improvement of the RPS activity as a whole. Third, a well-dimensioned and polyvalent refinery scheduling staff should be structured. Typically, a refinery scheduling team comprises four to eight schedulers, depending on the complexity of the refinery (Zhang and Valleur, 2010). The RPS technology can be implemented once Prerequisites I and II are secured.

III. **Appropriate system implementation strategy**. Irrespective of the RPS tool, successful RPS projects are based on increasing scope. A good strategy is to implement the RPS system while focusing on an important, yet simple, refinery area (e.g., the crude oil area). The entire refinery is not considered at once because doing so may result in numerous difficulties, thereby delaying the project, retarding the production of measurable benefits, and hence demotivating key people (the schedulers). Following scope definition, the first and arguably the *most important* step in implementation is understanding the real-world system to be represented in silico (typically four to eight months, depending on the complexity of the refinery). This step includes, for instance, obtaining in-depth knowledge on operational rules, plant topology, equipment capacities and operation modes, processing models, and crude oil characterization. This work should ideally be performed by an interdisciplinary consulting team that preferably consists of IT experts, OR specialists, and an experienced refinery staff with the most extensive knowledge of practical operations working in unison. Given that a large amount of information must be obtained and organized, having the right people at the right time is a key factor. Rework or, even worse, unserviceability may result if this step is skipped or haphazardly executed. The second step is system configuration, i.e., modeling the refinery system in the RPS application (weeks to months). Then, the corporate systems and databases are integrated (Zhang and Valleur, 2010), and the RPS system functions are subjected to offline evaluation tests (three to six months). The final steps are training (Joly et al., 2015) and mentoring in real-world settings ("assisted operation," weeks to months).

IV. **Appropriate refinery model maintenance strategy**. The RPS application mimics a complex engineering system (Ottino, 2003,2011) that adapts and evolves over time. For instance, business rules and processing models change, new raw materials and products are introduced in response to market opportunities or legal requirements, and refineries are periodically revamped to retain competitiveness in the ever-changing business environment. Therefore, the refinery model (as well as the entire RPS application) requires continuous updating and sophistication. If the model is not promptly updated or corrected, then the application may fail to predict critical events or expected behavior. As a result, schedulers will no longer trust the tool and will return to using Excel spreadsheets. Our experience has proven that prompt responses from the business consulting team to the schedulers are crucial (Joly, 2012). At Petrobras, good results were achieved through the implementation of a help desk service through which schedulers talked directly to the BR-SIPP support team. Thus far, we have discussed necessary but insufficient conditions.

V. **Excellence in human resources**. As adeptly indicated by Zhang and Valleur (2010), RPS requires “bright engineers and open minds to test new tools and to find new solutions.” For instance, ensuring that such personnel have theoretical background in OR is salutary. If the staff is unable to perform a critical technical analysis of the solution, then the RPS application may be reduced to a mere video game whose usage will be rendered costly and unfruitful by the trial-and-error approach. Education is key in this métier. Specialized knowledge related to the scheduling activity (and its computational tools) should not be restricted to a few personnel inside the refinery; otherwise, the sustainability of the RPS project will be endangered. In fact, good practices include some level of staff turnover with respect to individual functions performed by each one inside the planning or scheduling department. If the RPS technology is self-developed, then refinery schedulers and the RPS corporate project team should always collaborate. Encouraging continued education (e.g., M.Sc. and Ph.D. programs) in OR is effective in augmenting staff commitment and motivation (Kelly et al., 2014; Nishioka et al., 2012). In fact, implementing training programs in OR foundations in the industrial environment is a strategic action (Joly et al., 2015) that not only improves staff motivation in pursuing enhanced decision-making quality but also catalyzes change in cultures and paradigms. Paradigms are defined as a “set of theories, beliefs, values, instruments, and methods” (Thomas Kuhn quoted in Lenas and Luyten, 2011), which, according to Lenas and Luyten (2011), are “based on past scientific achievements that are acknowledged by a particular scientific community as the foundation of its research practice.” Introducing computer-aided decision-making technologies to the industrial environment may contest prior precepts. The scheduling department of oil refineries generally has a high profile in the organization because it is the “central nervous system” that commands the refinery operation. Typically, these personnel like challenges and, once equipped with efficient tools, search for new and profitable operating points. Thus, ancient premises, some of which may be only private viewpoints or mere operational myths, are tested. In fact, RPS is a paradigm-breaking activity and therefore should no longer be considered a mechanical execution of work by managers. If so, managers should be replaced.

VI. **Appropriate key performance indicator (KPI) model**. RPS is an interdisciplinary challenge that requires close collaboration among OR, IT, and process engineering experts, to cite a few. However, human and economic resources in the organization are limited; hence, the RPS system competes for resources with other refinery automation projects. Given that the most profitable projects normally receive the highest priority, calculating the benefits provided by the RPS project becomes crucial. However, formulating reliable KPIs for quantifying the decision-making quality of RPS is not a trivial task. A KPI should ideally be able to evaluate the actual economic gap between the new situation (with RPS system) and the previous one (without RPS system), thereby determining the RPS project payback. However, comparing both situations is impossible from a practical standpoint because the “blank” scenario (i.e., the refinery without the RPS project) no longer exists after the RPS project is implemented. The actual benefit provided by the RPS project may and generally will be greater than the benefit only related to the use of the RPS tool (i.e., the software itself). Working processes, corporate systems and databases, and staff training are typically improved when the RPS project is implemented. Therefore, although the RPS tool is deliberately switched off to artificially assess the benefits only related to the use of the RPS tool, calculating the true benefit associated with the RPS project remains difficult. In our experience, a reasonable, easily implementable, and relatively robust KPI model may be based on the plant profitability gap between the *planned* and the *observed* refinery performance with regard to a given time period in the past. In this study, the planned refinery performance calculated in silico is based on *known* information about the initial and bounding conditions of the model. In other words, the planned performance is determined by solving the problem instance configured using historical data instead of predicted ones. Aside from serving as a valid KPI for assessing the decision-making quality of RPS, the gap information may serve as a driving force for implementing enhancements in the planning model with respect to modeling accuracy and integration with scheduling. Incoherent or antagonistic KPIs may be preexisting in complex, multi-departmental organizations, such as oil companies. Thus, RPS projects are a formidable catalyst that can resolve this problem.

## 2.2 Do not underestimate the complexity of RPS

Despite being a vital technology for achieving safe and profitable plant operation, RPS remains an open question from the industrial and academic standpoints. Most, if not all, commercial solutions devoted to supporting refinery schedulers are currently based on event-based simulation technology (Table 2). Although many of these excellent tools embed some optimization technology, the scope of the problem that can be solved through optimization remains typically limited to a few subsystems of the refinery (e.g., crude oil area and/or blending units). Commercially available RPS tools can provide only converged solutions that are not optimized at all. By contrast, specialized modeling platforms for process industries, such as IMPL by Industrial Algorithms, are arguably promising methods for achieving such a high goal. Aside from relying on cutting-edge optimization technologies, these tools are flexible enough to adjust the trade-off between model complexity (i.e., computational cost) and model usefulness. However, RPS currently

**Table 2** Commercial decision-making technologies applicable to RPS

| Vendor | Solution |
|---|---|
| Aspen Technology | Aspen Petroleum Scheduler |
| Haverly Systems | H/SCHED |
| Industrial Algorithms | IMPL[a)] |
| Invensys | Spiral Schedule |
| Princeps | Flowers |
| Prometheus | PROLAV |
| Soteica | Visual Mesa |
| Technip | Forward C |

[a)]IMPL is a modeling platform for process industries

remains one of, if not the most, challenging layers of refinery automation.

The problem is inherently difficult in mathematical terms. RPS aims to obtain a feasible set of operational actions throughout a predefined time horizon in the light of the macroscopic targets previously defined at the planning level (Fig. 1). In other words, RPS should "unfold" optimal guidelines into feasible orders, which must be operationally executable (Joly and Pinto, 2003; Joly et al., 2002). Typically, distinctions between modeling approaches may comprise differentiated representations of refinery resources (e.g., aggregated tankage in planning replaced with individual tanks in scheduling) and process models (e.g., approximated linear models in planning replaced with nonlinear or rigorous process models in scheduling). Moreover, additional model variables (e.g., for representing intermediate streams, additives, utilities, or product qualities) and constraints (e.g., specialized operational rules indicating the need for integer variables) are usually combined with a different technical-economic objective function in RPS. Consequently, RPS takes the form of large-scale optimization problems in which important nonlinearities (e.g., rigorous or semi-rigorous processing models and accurate blending models) are conjugated to the combinatorial enumeration of several operational possibilities in the form of discrete decisions (e.g., resource selection and sequencing over time). Such characteristics render these optimization problems nondeterministic polynomial time hard problems (Garey and Johnson, 1979) (Fig. 2). Therefore, computational complexity is another high-profile challenge in RPS, which becomes even more relevant if oil refineries are considered typically part of a nervous supply chain system in which business premises may suddenly change during crisis situations. New decisions can result in drastic economic and operational consequences if overly cautiously and not promptly scheduled.

RPS deals with an astonishing amount of information, thereby making itself look like an information-hungry "monster" from a business perspective. Moreover, the RPS solution must present a high and harmonic interconnectivity for integration with corporate databases and business solutions to be operable in real-world settings. Data from several refinery departments and corporate areas must be known a priori to run an RPS application (Fig. 3). At the least, these data comprise information regarding (a) the quantity and quality of inventories (tank farm) and connecting modals (e.g., long pipelines and terminals) (b) material receipts and dispatches under execution, (c)

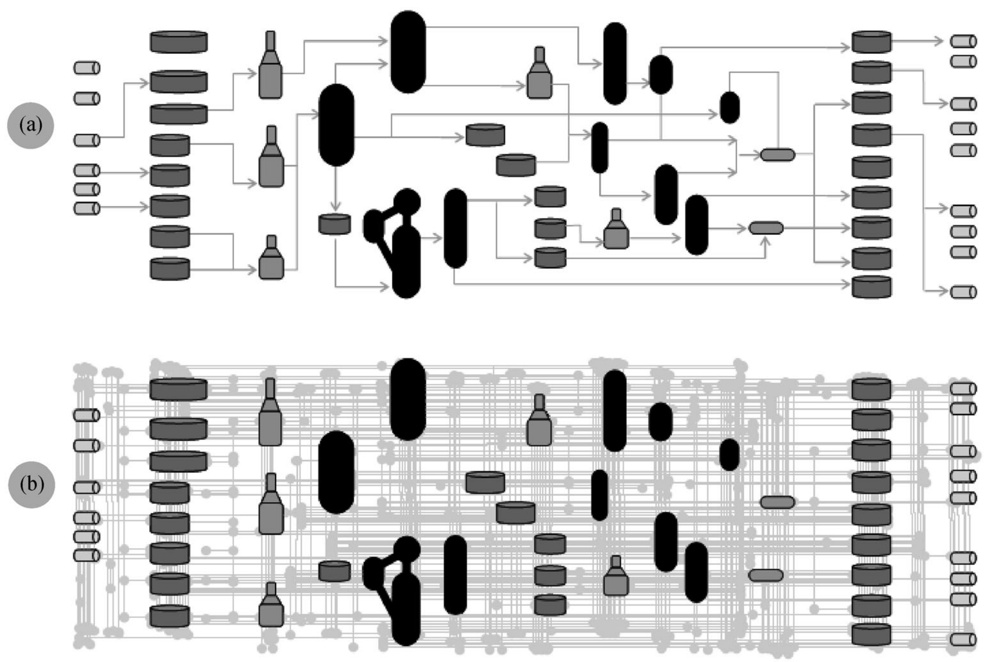
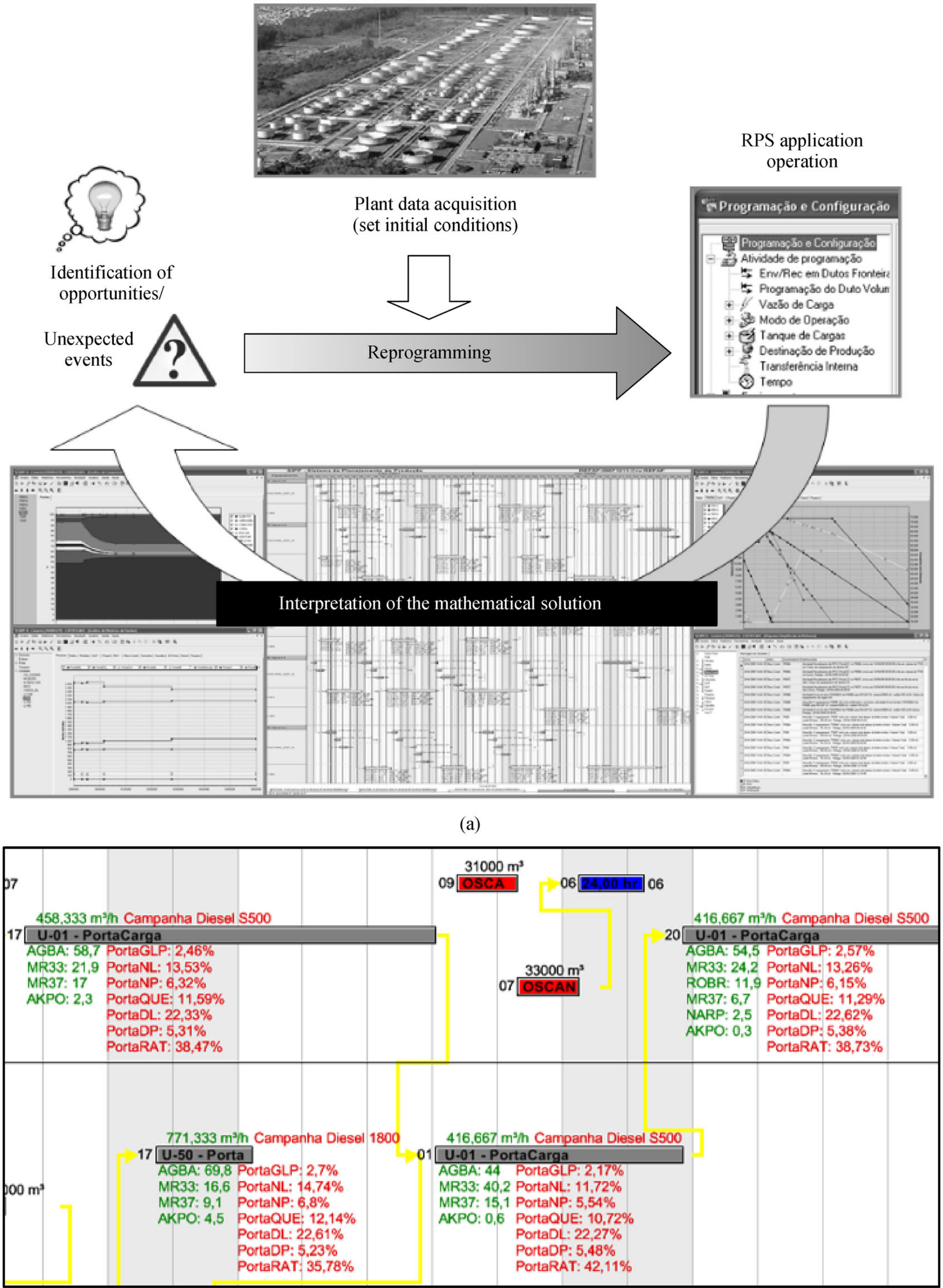



**Fig. 2** A quick look at the problem: (a) May lead to an understatement of the actual complexity of (b) the refinery production scheduling (RPS) problem

critical active alignments and blending operations in course, (d) actual unit operation modes and corresponding feed flow rates, (e) current economic data, and (f) updated maintenance schedule of critical equipment. This data set, which forms a true photograph of the plant at a given but generally suitable time instant, defines the initial conditions of the problem. A movie, i.e., a feasible schedule for plant operation throughout a predefined time horizon, will be made or remade from this photograph. Therefore, the initial condition of the problem has to be automatically




(a)

(b)

**Fig. 3** (a) Operation cycle of an RPS application based on event-based simulation technology; (b) enlarged details of the Gantt chart depicting scheduling information (e.g., crude oil composition, batch size and flow rates, operation modes of crude distillation units, and expected crude yields) obtained from structured databases and systems to efficiently and reliably run the RPS system.

Once a solution for the scheduling problem is determined, it should then be efficiently and reliably implemented by online applications devoted to supporting the refinery operation. These applications include advanced process controllers (APCs) (Pinotti et al., 2008) and real-time optimizers (RTO) (Liporace et al., 2009), as well as several specialized applications, such as in-line blending (ILB) and in-line certification (Feital et al., 2013). In other words, system integration is crucial in any successful RPS application. First, the amount of manual work required to feed into and to extract data from the RPS application may be impractical. Most importantly, data reliability can be compromised. Phone calls do not substitute system integration. Oral communication does not comply with the from-to relationships related to critical information and does not allow for reliable and structured data registration or traceability. Second, poor system integration results in costly rescheduling operations.

Frequent rescheduling is undesirable, but it may happen because of at least four causes. The first reason is that consistent scheduling can only result from good planning (Kelly and Mann, 2003). If the planning model has poor adherence to the plant, then its operationalization at the scheduling layer becomes infeasible. The second reason is reduced compliance of the scheduling model with the plant, which, in turn, may be the outcome of poor model maintenance. The third reason is operational, logistical, and commercial uncertainties. The fourth reason is the complexity of the refinery operation. Analogous to a living organism, a real-world oil refinery is interfaced with the external environment, thereby representing an open system. However, the only propositions based on pure mathematics and logic that can be verified are those concerning closed systems. Consequently, our knowledge of refineries will always be only partial or approximate at best (Horgan, 1995). On the one hand, simple rules underlie many complicated phenomena. On the other hand, open systems require input parameters and assumptions that are not completely known. Even when measurements are available, they are unavailable for all model elements. The scaling up of nonadditive properties among distinct time and length scales (from seconds to weeks and from molecules to the entire plant) introduces additional difficulties to ascribing properties for modeling the components of the system (Ottino, 2003). Therefore, having a methodic routine for model maintenance is strongly recommended. Although the refinery scheduling model may be considered a caricature of reality, "a model, like a novel, may be convincing" (Oreskes et al., 1994). Therefore, if model maintenance is neglected, then the solution output from the RPS application may become unreliable. If the scheduler is unaware of this neglect, then incorrect operational instructions might eventually be implemented.

### 2.3 Eliminate gaps in knowledge as they may crystallize paradigms

The term "optimization" has become popular in the modern industrial environment. However, although a heavily used word, optimization has not been studied extensively and is not always understood. Examples are numerous.

"Classical" mistakes are typically based on ancient paradigms, such as guidelines for operating the unit or plant at maximum load, instead of the optimum, all the time. In fact, "beating the record" has propelled the managerial career of many and hence has become an obsession to some. This scenario reveals how optimization is sometimes still treated with scorn by leaders in the organization, thereby potentially leading to a conspicuous repertoire of harmful consequences for business performance. For instance, if one neglects the dynamicity of logistic constraints to which the refinery is subject to along the scheduling horizon (e.g., storage capacity in the refinery tank farm and availability of supply chain oil pipelines), then the quality of high-value-adding products will naturally be degraded. In addition, such unfavorable practices may render OR-based tools mere simulators instead of true optimizers, with short-term economic losses of several million dollars (Kelly and Mann, 2003).

"Sophisticated" mistakes may involve optimization theory concepts. A representative example is the erroneous understanding of marginal value, which is among the most important concepts in LP. Marginal value denotes the mathematical derivative or sensitivity of the objective function as a function of an independent model variable in an active constraint around the optimal solution. Right after the pioneer application of LP techniques during World War II in the 1950s, marginal value was promptly incorporated into the oil industry vocabulary (Symonds, 1955). Unavoidably, this term became a popular technical term in the engineering departments of oil refineries following the introduction of LP-based commercial solutions for refinery planning in the 1970s (e.g., Bonner and Moore, 1979). In a typical hierarchical decision-making framework, as depicted in Fig. 1, marginal values play a key role in the integration of two adjacent business layers. In this study, marginal values determined at a given layer represent the optimization drive for the subsequent hierarchically inferior and mathematically detailed layer. For example, RPS should be run based on marginal values or cost determined at the refinery planning level in cost analysis. Misunderstandings about marginal value may result in the deliberate use of a particular set of marginal values typically related to the optimal solution of strategic or tactical planning as an optimization drive for running online applications, such as RTO or APC applications, given that LP-based tools for supply chain and refinery planning are well established in the oil industry. Subsequently, the theoretical link between offline (refinery planning and scheduling) and online (RTO and APC) optimization layers (Fig. 1) is broken. An even worse scenario is when distinct economic drives are confounded, which may occur when an incomplete set of marginal values is supplemented with product sale prices to complete the economic data set required to run the optimization application. In this case, the optimization drive becomes inconsistent.

However, the perverse outcomes related to the misunderstanding of marginal value go beyond the above-mentioned cases. Another class of high-profile optimization problems, the optimization drive of which may also be based on marginal value information, comprises technical-economic assessments of large-scale projects, such as refinery revamps or enterprise-wide supply chain logistics. In this case, the use of known marginal values, which are typically based on the current bounding conditions, must be carefully considered in economic analyses related to new scenarios far from the optimal point that the marginal information is associated with. In other words, the fact that marginal values are not subject to extrapolation must not be ignored. Such mistakes may have drastic outcomes, with economic losses reaching billions of dollars. As indicated by Michael Oakeshott in his 1933 "Experience and Its Modes," "Confusion, ignoratio elenchi, is itself the most fatal of errors, and that it occurs whenever argument or interference passes from one world of experience to another." (quoted in Lenas and Luyten, 2011).

### 2.4 Know the threats and their causal relationships

Petrobras has been exerting research effort since the 1990s about the development of innovative short-term production scheduling technologies to improve the integrated performance of the plant (from crude receipt to product delivery) (Magalhães et al., 1998). Although ambitious inroads in the field of optimization were started long ago (Pinto et al., 2000; Joly and Pinto, 2003), the current status of the RPS activity at Petrobras, in its best form, is still based on event-based simulation technology. Despite the fact that optimization technology has increasingly been adopted in novel self-developed industrial automation projects, such as the GOMM project (Moro and Zanin, 2014), the scope that can be solved through optimization remains circumscribed (e.g., product blending scheduling).

Meanwhile, the major by-product of this exciting enterprise, which led to the production of BR-SIPP technology, among others, is a comprehensive apprenticeship. Our experience showed that specialized expertise from diverse domains (e.g., chemical engineering, OR, and IT, to name a few) should be appropriately integrated and operationally supported in real time during all phases of the RPS project. The success or failure of an RPS project is a function of numerous aspects whose causality relationships are schematically depicted in Fig. 4 and structurally discussed in Table 3.

## 3 Discussion and conclusions

In line with the Industry 4.0 agenda (Lasi et al., 2014; Lee et al., 2015), the moneymaking field of industrial automation is now experiencing a critical stage in the process industry. Nonintegrated automation systems and manual decision-making processes that rely on human knowledge and experience for plant operation are increasingly being replaced by integrated cybernetic frameworks that are based on novel advanced artificial intelligence techniques (Monostori, 2014; Scheuermann et al., 2015). Such a revolution is accompanied by novel and highly complex refinery operation management approaches (e.g., petroleomics (Xu and Shi, 2016)), which aim to capture existing economic opportunities in the oil industry supply chain by regarding them as coupled networks of dynamically interacting systems in a wide range of length scales.

From a business management standpoint, the outcome is clear. The refining business is now faced with a new array of chemical engineering challenges that would have been unthinkable only a couple of years ago. Although profitability remains the priority and safe operation a premise, the central tenet of plant management, which was previously reductionist, has changed. By envisioning oil refineries as truly complex open systems, their operation can no longer be understood by investigating their fundamental components in isolation. The essence of such systems lies in the intricate and usually nonlinear interaction among their building blocks, be they of physical, technological, or human nature, from which the overall behavior of the system emerges (Ottino, 2003; 2011).

Therefore, developing or buying a commercial solution (the software itself) is an insufficient solution to real-world short-term scheduling problems of oil refineries. RPS is a highly integrative activity that requires the entire organization working together to do "the right thing the first time."

Ever-changing and multi-priority environments are hallmarks of oil refineries. However, we argue that RPS must always be the focus of attention. If costs can be minimized when unfavorable economic scenarios arise, then surely the investment on RPS should not be cut. No other refinery automation project has greater economic return than the RPS. Although potential economic benefits may depend on the complexity of the refinery (great opportunities generally being associated with complex refining schemes), conservative estimates are of the order of 10 million USD per year for a conventional, medium-sized refinery (Moro, 2003). However, critical production subsystems of the refinery may have substantial economic

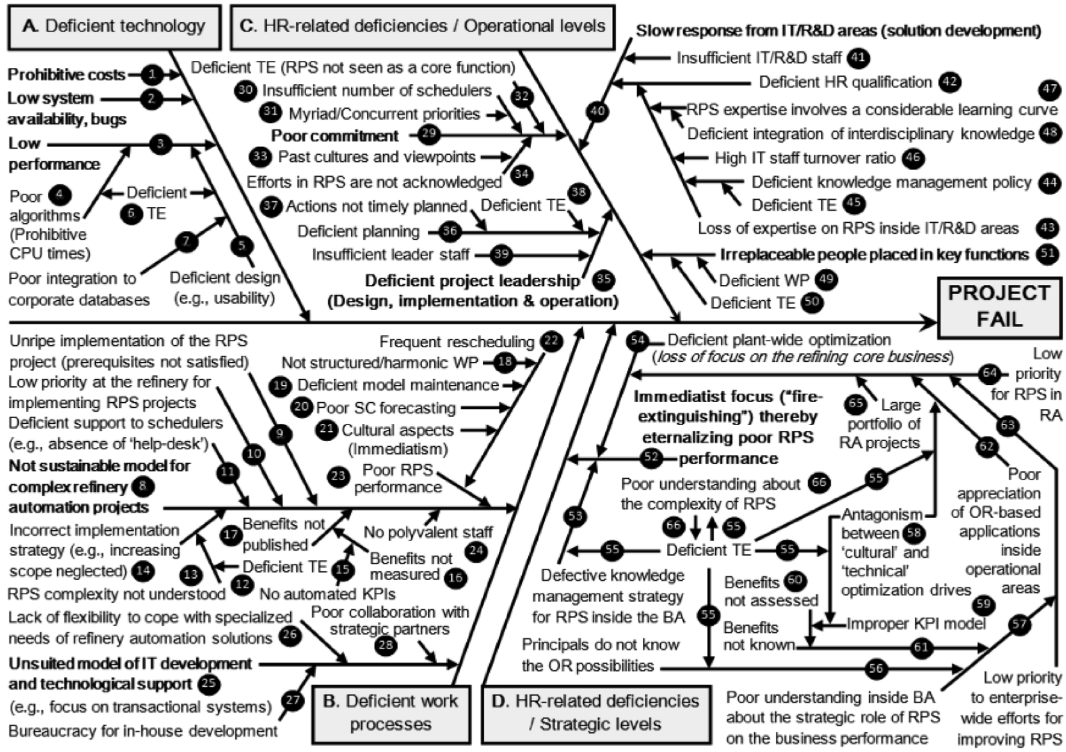



**Fig. 4** Ishikawa diagram showing the key relationships among potential factors that may cause overall project failure. *Abbreviations*: BA, business area; CPU, central processing unit; DMQ, decision-making quality; HR, human resources; IT, information technology; KPI, key performance indicator; OR, operations research; R&D, research and development; TE, technical education

**Table 3** Potential factors that may threaten an RPS project

| Threat | Potential factors |
| --- | --- |
| A. Deficient technology | (1) Prohibitive investments in software (e.g., acquisition or licensing costs); |
| | (2) Operational problems related to system failure (e.g., bugs) or availability; |
| | (3) Poor computational performance due to (4) costly computation;<br>(5) System inadequacy in meeting the needs of schedulers (e.g., poor usability and navigability), which may arise from (6) deficient know-how about RPS and related disciplines, such as operations research (OR); |
| | (7) Deficient integration of the RPS solution into corporate systems and databases, thereby possibly causing prohibitive manual workload, which renders RPS impractical; |
| B. Deficient working processes | (8) Failure to meet certain prerequisites for achieving sustainability;<br>(9) Mature bounding conditions related to database infrastructure building;<br>(10) Local priority at the refinery in the early phases of the RPS project (right people at the right time);<br>(11) Availability of a corporate scheduling support team that can respond quickly to schedulers with regard to technological questions concerning the RPS application (from simple usage doubts up to requests for technology sophistication); |
| | (12) Unavailability of a consulting team with a clear understanding of the RPS project purpose, capabilities, limitations, and (13) complexity as an interdisciplinary activity in which several actors must work together to accomplish desired goals; |
| | (14) Improper implementation strategy, which fails to speed up the production of tangible benefits (e.g., good practices recommend the adoption of increasing scope over time); |
| | (15) The lack of a consistent and automatized (as much as possible) key performance indicator (KPI) model for assessing the decision-making quality in RPS (Fig. 5); if tangible benefits associated with the RPS project are not measured (16) and evidenced (17), then continued investments on RPS may not occur, thereby compromising project sustainability (8); |
| | (18) Ineffective working processes combined with<br>(19) Undisciplined practices for model maintenance,<br>(20) Poor corporate foresight concerning the supply chain operation,<br>(21) Immediatism (high priority for short-term results at the expense of long-term benefits normally associated with good decision making, which may indicate high rates of rescheduling (22) and poor RPS performance (23), thereby compromising the sustainability of the RPS project (8), and (24) "Irreplaceable" people playing key roles in the RPS project; |

(*Continued*)

| Threat | Potential factors |
|---|---|
| | (25) Improper software development model, which neglects the fact that refinery automation systems require approaches different from those applied to conventional (e.g., transactional) IT systems;<br>(26) In this study, agile (i.e., not bureaucratized [27]) software development methods should be considered to strengthen the collaboration between the organization and third parties (e.g., technology companies and universities) in the appropriate working structure (e.g., center of excellence) (28); |
| C. HR-related deficiencies at operational levels | (29) Low commitment, which may be unavoidable if the refinery is understaffed (30) and/or highly demanded at the time of project implementation (31); |
| | (32) Deficient technical education (i.e., lack of managerial understanding of the strategic significance of OR for the modern refining business), which underscores unfruitful bounding conditions (33) for developing costly actions devoted to improving the decision-making quality (34); |
| | (35) Deficient project leadership by a corporate consulting team, which may also introduce serious obstacles for achieving and sustaining success in RPS projects;<br>(36) Deficient planning for implementing this kind of project, which emerges from the lack of timely and integrated actions involving many actors (37) or the poor expertise or experience of the leading staff (38), which must be appropriately sized and multidisciplinary (e.g., backup personnel should be available) (39); |
| | (40) Reduced celerity from these technological areas to satisfy the short- and long-term needs of RPS system users, which may be due to insufficient human resources (41) or deficient HR qualifications (42); |
| | (43) Loss of RPS expertise in the IT and R&D areas, which can be solved by adopting efficient knowledge management policies (44) that consider the importance of continuous learning (e.g., advanced educational programs and participation in technological consortia) (45) for achieving excellence and increasing staff motivation; |
| | (46) Volatility of valuable human resource;<br>(47) Costly learning curve normally associated with the RPS activity, which is particularly problematic if the staff does not have preexisting interdisciplinary expertise (48), and is an additional factor that negatively contributes to the sustainability of excellence in human resource qualifications (42); |
| | (49) Deficient work processes and educational policies (50), which may produce "irreplaceable" people in the IT and R&D departments (51), thereby causing project failure; |
| D. HR-related deficiencies at strategic levels | (52) Immediatism, which is a well-known threat to RPS projects, from conception to operation, the hallmark of deficient strategies for knowledge management at the highest levels of the corporation (53), and is among the major nontechnical reasons for poor plant-wide optimization (54);<br>(55) Deficient technical education at the managerial level, which damages business performance given that principals are responsible for strategic definitions; |
| | (56) Principals who do not know about OR possibilities and cause the strategic role of OR in refining the business to not be acknowledged in the highest levels of the company (57); |
| | (58) Cultures and myths that are still present in the minds of some individuals (e.g., "maximal load indicates maximal profit"), which may result in the design of improper KPI models (59) that hinder the accurate measurement of RPS benefits (60, 61), thereby causing poor appreciation of OR-based technology within operational environments (62) and leading to a global result that is of low priority to enterprise-wide efforts in developing the RPS activity in business areas (63), as well as in technological areas (64), where RPS projects compete for available resources with other corporate projects (65) |

opportunities. Several researchers argue that blending operations are the refinery's "last chance" to influence profitability. Examples include the scheduling of ILB units devoted to optimizing the blend mix that feeds a process unit or to minimizing the product quality giveaway of finished oil products (typical benefits of 1.00 USD per barrel of processed crude or more, according to our experience). In conclusion, without actions planned in light of long-term policy for refinery automation, the RPS project will fail or become ephemeral at best.

Figure 4 shows a number of issues, some of which are either processes themselves or aspects that can be related to another specific process not explicitly considered in this cause–effect diagram. Overall, these processes form a value-added chain through which technical and economic information is processed and transformed into an operational production schedule. Such processes can, in principle, be categorized into three classes, namely, real-value-adding (RVA), business-value-adding (BVA), and non-value-adding (NVA) processes. Processes that directly affect the quality of the mathematical solution, i.e., processes that contribute to produce a "good" production schedule (the solution output), are RVA processes. Examples of RVA processes include algorithms and computational processing. Processes that satisfy business requirements but do not add value from the scheduler's viewpoint are BVA processes. Illustrative examples of BVA processes are preparing solution reports and knowledge management policies. Finally, processes that do not enhance the quality of the schedule and do not support the business process are NVA processes. These processes are also referred to as waste processes and often indicate deficiencies in the value-added chain model (NVA processes can be removed with no effect on the solution quality.). Examples of NVA processes are inspection and approval processes.

In our experience, successfully obtaining the RPS solution will provide permanent opportunities to optimize the entire value-added chain by eliminating NVA processes. Among the foremost roles of the head of the RPS project is periodically analyzing branches B, C, and D (Fig. 4) while identifying processes that can be suppressed, if any. NVA processes may emerge over time from cultural or operational paradigms, deficient technical education, and/or gaps in working processes.

We therefore conclude that

• Acquiring or developing a good computational solution (the RPS software itself) is not sufficient for achieving a successful RPS project. To be successful, the RPS project also requires

• Satisfying IT prerequisites, such as data organization and structuration in corporate databases and systems, and providing system integration. The hallmarks of RPS projects with neglected IT prerequisites are (a) prohibitive human resources that operate the RPS application and (b) loss of market and logistic opportunities due to the non-timely delivery of the required data for RPS application execution, delayed scheduler response, or poor solution quality.

• Adopting the appropriate strategies for implementing the RPS project. These strategies include (a) considering increasing plant scope and (b) ensuring that the right people are in the right place at the right time for efficiently executing refinery modeling, system configuration, solution validation, instructive training, and start-up assistance.

• Adopting the appropriate strategies for RPS system maintenance. Schedulers demand timely, rapid, and efficient support; otherwise, they abandon the application and return to their Excel-like spreadsheets. Thus, prompt response from a highly specialized consulting team, which is usually composed of the organization's people and third parties working in unison, is required. In this sense, adopting a corporate "help desk" support model should be considered.

• Achieving excellence in human resources. The sustainability of a successful RPS project is the outcome of a virtuous cycle, which is grounded on technical education of qualified and experienced staff (Fig. 5). Education is a significant catalyst for implementing and improving RPS (Arrows 1 to 4, Fig. 5) and ensuring its sustainability (Arrows 5 and 6, Fig. 5).

• Managerial priority to the RPS activity is not a major prerequisite; instead, it is the natural outcome of a sustainable RPS project whose performance is appropriately monitored.

• Maintaining an advanced RPS solution in real-world settings requires optimizing the entire value-added chain permanently. The goal is to eliminate NVA processes, which typically germinate from misleading organizational cultures, operational paradigms, and gaps in technical education and/or in working processes.

Our general recommendations are as follows:

• Organizational philosophies and operational paradigms should continuously be reassessed to banish any awry "imaginary constraint" from pushing the operating point away from the mathematical optimum. For instance, optimizing individual variables (e.g., maximizing the refinery load) to meet subjective goals can generally do ruin the technical work of a professional team committed to determining the best operating point of the plant in an integrated manner.

• RPS-related working processes should continuously be reassessed inside the organization to improve their effectiveness and efficiency. In particular, working processes should be:

• Standardized and consistent and should not have gaps or scope overlaps and

• Strongly based on system integration, thereby

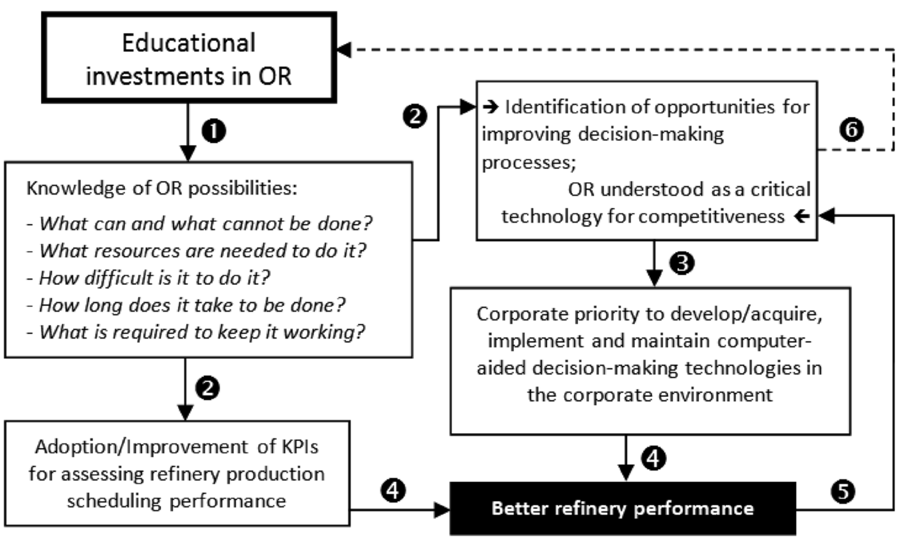



**Fig. 5** Educational actions in operations research (OR) are strategic for the successful implementation of supply chain optimization projects

enabling timely, reliable, and traceable information flow among corporate agents. Phone calls and Excel-like spreadsheets should be minimized.

The conclusions and recommendations are technically supported by improved results in terms of KPIs (see Joly, 2012). The operationalization of the recommendations proposed should be led by the head of the business area (generally an experienced process engineer), who must be part of the RPS project consulting team. Given that real-world OR projects are inherently interdisciplinary, we believe that our conclusions can at least be partially extended to other complex OR projects in several engineering branches, thereby making this report appealing to a broad audience.

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