

## **Integration of maintenance and production strategies under subcontracting constraint: Classification and opportunity**

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### **ABSTRACT**

The main concern of the manufacturing industry is maintaining the tools of production so that they are in good working order. However, the maintenance and production functions are linked because the integrated management of these two functions is necessary for the efficient operation of the means of production. In fact, when the demand exceeds the maximum production capacity, the company takes on subcontracting to meet the needs of the customers. The objective of this research is to identify the current and future direction of research in this field according to the different classification criteria proposed. In this paper, firstly, the different approaches of maintenance integrated into production systems are presented. Secondly, the models that deal with joint maintenance management and subcontracting production as a solution that aligns with the company's strategic objectives are discussed as well as the resolution and management approaches that integrated problem optimisation. Finally, a comparative study of existing approaches was conducted and their purpose analysed. As perspective, we will propose and implement in our future research a model and powerful tool to establish a better policy of maintenance integrated to the production using subcontracting.

**Keywords:** Production; maintenance; coupling; subcontracting; optimisation.

### **INTRODUCTION**

The current manufacturing industry is characterised by strong competition to satisfy the needs of a clientele that is often demanding in terms of quality, cost, turnaround time and safety. To remain competitive, companies must control operating costs and optimise production facilities. To keep a good image of the company, it is necessary to respect the delivery time and the conformity of the customer's requirements. At the same time, it is necessary to develop technical strategies that improve the equipment productivity and availability because integrated maintenance combines both production and maintenance management (Figure 1). In the literature, several research studies have been carried out to confront the hybrid management of maintenance and production. The objectives of reference work [1] are to establish an economic production plan, as well as an optimal maintenance strategy in a sequential manner, minimising the total cost of production/inventory and the cost of maintenance. Then, the authors of reference [2] studied the integration of scheduling decisions in the case of a single machine for production and maintenance operations to, simultaneously; minimise production costs

and maintenance costs. In addition, [3, 4] treated maintenance and production management in a joint way. Based on a semi-Markovian decision process and the stochastic dynamic programming method, the authors in [5] presented a model of interaction between maintenance and production. From that perspective, they have determined optimal production, repair/replacement and preventive maintenance policies for a degraded manufacturing system.

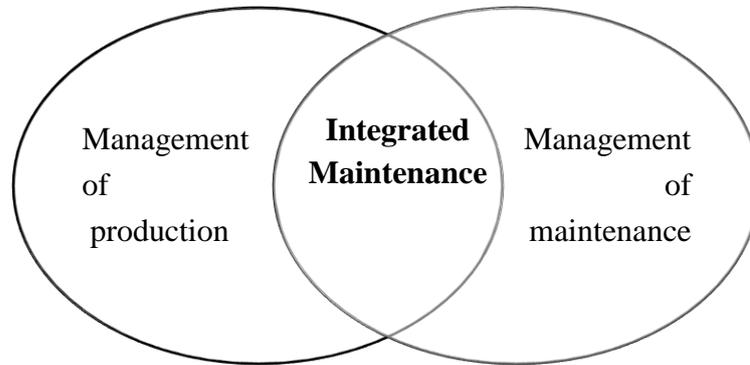


Figure1. The concept of maintenance integrated into production systems.

Sometimes, the integrated production and maintenance strategies are insufficient to minimise maintenance and operating costs in order to increase the availability of production systems and especially to meet a demand that is often diversified and superior to the maximum capacity of production. In such a situation where the company is forced to satisfy a demand that exceeds its production limits and to win new markets or just to preserve these potential customers, the company is obliged to resort to the outsourcing of the production system, which consists transferring all or a part of the quantity to be produced to an external partner [6, 7]. The main industries considered are the automobile industry, the field of transport of petroleum products and the aeronautics industry. The structure of this paper is as follows. After presenting the models that have dealt with the joint management of maintenance and production, we are dealing with the approaches to solve problems of joint optimisation of maintenance and production by introducing a comparative analysis of integrated maintenance models under subcontracting constraints. This leads to the identification of future research prospects.

## **METHODS AND MATERIALS**

Effective bibliographic research requires an adequate research methodology. With the aim to cover the subject of integrated subcontracting maintenance, we opted for a literature review based on a database containing articles, conference papers and doctoral theses. As for the bibliography on integrated maintenance for production under subcontracting constraints, we have adopted several databases: Taylor & Francis, Scopus, Thomson, Springer, Elsevier, Science Direct, IEEE Explore and Emerald Insight. We took note that the literature search was initiated on the descriptors "Integrated Maintenance" and "Subcontracting". In addition, several combinations of the above descriptors have also been developed to ensure correct and relevant results. After reviewing the literature, we have found 105 papers (5 doctoral reports and 103 scientific papers). Figure 2 shows the classification of references by year of publication.

Table 1. Distribution of references according to the source.

Source	Number	% of the total
International Journal of Production Research	21	19
European Journal of Operational Research	7	6
International Journal of Productivity and Quality Management	1	1
Naval Research Logistics	1	1
Computers and Industrial Engineering	7	7
IEEE Transactions on Reliability	1	1
Journal of Decision Systems	1	1
International Journal of Production Economics	11	11
Journal of Intelligent Manufacturing	2	2
MOSIM'01	1	1
Information Sciences	1	1
Interfaces	1	1
INCOM'09	2	2
IIE transactions	4	4
International Journal Mathematics In Operational Research	1	1
MOSIM'10	2	2
Mathematical Problems In Engineering	1	1
Computers and Operations Research	4	4
OMEGA-International Journal of Management Science	2	2
Journal of Quality In Maintenance Engineering	4	4
International Conference on Industrial Engineering and Production Management	2	2
IEEE Conference on Automation Science and Engineering	3	3
IFAC Papers Online	2	2
Journal of The Operational Research Society	1	1
CIRP Annals- Manufacturing Technology	2	2
Reliability Engineering and System Safety	4	4
International Journal Advanced Manufacturing Technology	2	2
International Journal Advanced Operations Management	1	1
IFAC'11	3	3
International Journal of Management Science and Engineering Management	1	1
International Journal and Systems Engineering	1	1
Journal Européen des systèmes Automatisés (JESA)	1	1
SysTol'10	1	1
Applied numerical mathematics	1	1
Mathematical and Computer Modelling	1	1
EcoDesin'99	1	1
Total	103	100

As shown in Table 1, a group of three journals represents 37.00% of the references included in this work: International Journal of Production Research (19 references), International Journal of Production Economics (11 references) and Computers and Industrial Engineering (7 references). They were followed by the

European Journal of Operational Research (6 references) and Reliability Engineering and System Safety (4 references) which represent a 10.00% set of the examined items. The remaining 31 journals published comprised of 53.00% of the total considered references. Most of the problems of joint management of production and maintenance strategies have recently generated an increasingly fertile field for research as the number of publications has increased in recent years (Figure 2). Beyond that, from integrated maintenance to production, several research studies have considered the subcontracting constraint of production as a favourable solution that satisfies the requirements of the customer.

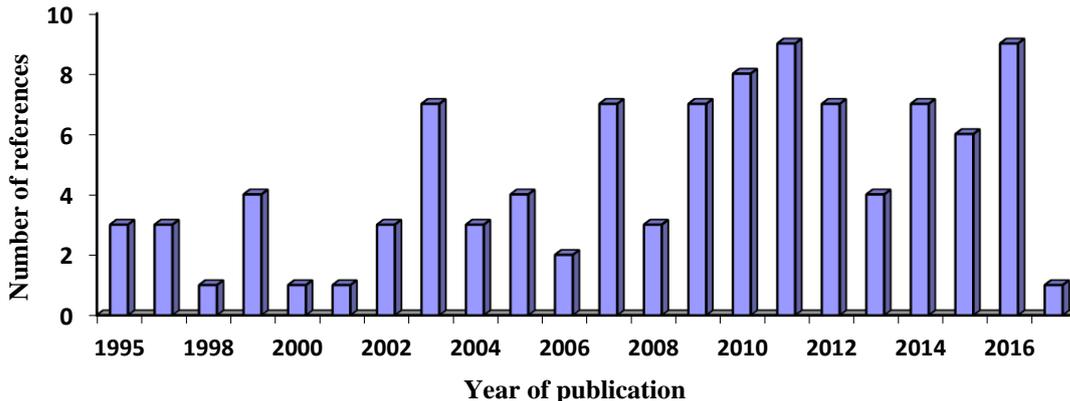


Figure 2. Sorting by year of publication.

### **Separate Management of Maintenance and Production**

Separate management of maintenance and production is manifested at the point where maintenance management does not consider the impact of production constraints and vice versa. Therefore, maintenance is often seen as a source of additional disruption to production and a cost function only, since both functions are always in conflict at the planning level as well as at the level of resource sharing. In addition, separate management of maintenance and production can lead to failure to comply with the preventive maintenance plan, resulting in the failure of production system equipment and failure to meet customer requirements, essentially in terms of delay, since compliance with the deadline is a high priority on the part of clients. The main challenge facing manufacturing is to produce more products using fewer resources [8].

The overlap between maintenance interventions and production operations is manifested at the production planning level, which requires the maximum availability of equipment as well as the maintenance planning that awaits production shutdown to carry out preventive maintenance interventions. The literature has treated the problem separately by considering each axis individually (production and maintenance). Given the models, either maintenance plans or production planning, reference [9] dealt with production planning, which consisted of satisfying customer orders by integrating quality to remain competitive. Moreover, the models of maintenance planning carried out in the literature did not explicitly consider their impact on production planning. Similarly, most production planning models do not consider the impact of corrective maintenance actions and preventive maintenance actions on their planning. Some authors proposed preventive maintenance policies regarding the critical age of the machine by comparing maintenance strategies to evaluate the performance of faulty production systems [10-12]. Similarly, the control of production systems under preventive maintenance was dealt with [13, 14] by developing an approach based on the Markov modelling.



minimise the cost of overhead and maintenance. In this sense, reference [26] amounted to simultaneously optimising the flows of production and preventive maintenance. The approach developed allowed considering the interaction between the maintenance strategy and the control policy. Other authors [27] proposed an extended linear programming model to calculate the optimal production plan with a minimum total cost. The problem of the dual objective of production planning and maintenance was treated as a mixed linear program. Some authors [28] presented the optimisation of preventive maintenance by a simulation model that combined maintenance and production. The intention was to simultaneously ensure a low frequency of failure by efficient periodic preventive maintenance and to minimise the unavailability of the production system, which implied a minimum impact on production. In the same context, reference [29] developed a combination of production and maintenance plan for a manufacturing system that satisfied a random demand. Joint optimisation was carried out to establish an optimal strategy for production and maintenance. The aim of [30] was to establish an economic production plan that satisfied a random demand, and an optimal preventive maintenance plan using the production plan was already established.

The second category developed models for joint planning of production and maintenance. However, the performance of maintenance and production management required their cooperation. The work of reference [31] dealt with the problem of maintenance planning. They offered some answers to the problem of the joint and integrated planning of maintenance and production tasks. Other authors [32] presented an integrated model of preventive maintenance production and planning for multi-state systems. On the production side, the model generated, for each product and production planning period, the quantity of inventory and the delivery time. On the maintenance side of each component, they proposed the time of each preventive maintenance action that can be carried out during the planning period of production. This is notably the case of reference [33], which addressed the problem of production planning, interacting with the environmental issue from a perspective of degradation by proposing and studying three production control policies and those of the revision policy concerning maintenance activities. The work by [34] focused on an integrated modelling method that simultaneously determined production planning and maintenance planning in the machining system, considering the replacement of the machine's failure tool, as well as the constant demand and possible shortage. Based on a linear mixed number programming model, the authors of reference [35] jointly planned the production and maintenance activities. The model considered the reliability (expected number of failures) of production costs, maintenance, shortages and demand. Preventive maintenance was performed on predetermined dates while corrective maintenance was performed to restore the system to an operating state without altering the failure rate function. In the same way, the aim was also to combine production and maintenance planning, this time in the context of a multi-product batch production system with faulty equipment [36]. Other authors [37] proposed joint production and maintenance models considering the uncertainty of yield, which helped avoid shortage of inventory and loss of customers. They formulated an integrated planning problem as a Markov decision process. In addition, they demonstrated that optimal production and maintenance policies had a control limit structure. The work by [38] dealt with integrated modelling of the scheduling of preventive maintenance and production activities. The reference [39] presented a joint model of production and maintenance planning for a production system subject to random failures. This model both reduced the shortage of demand and gave more flexibility to preventive maintenance actions.

Table 2. Synthesis of integrated maintenance approaches to production

Approaches	Authors
Optimisation of production and preventive maintenance policy	Van der Duyn and Vanneste [13], Meller and Kim [14], Salameh et al. [40], Ouali et al.[26], El-Kassar and Salameh [41] , Rezg et al.[42], Chelbi and Ai't Kadi [43], Kenné and al [44], Srinivasan and Lee [45], Yalaoui and Chaabi [27], Roux et al.[28], Hajej and Dellagi [29], Bergeron et al. [19], Gharbi and Kenne [18], Hajej et al. [30], Weinstein and Chung [46], Yao et al. [47], Iravani and Duenyas [48], Gharbi et al. [49], Liao et al. [50], Berthaut et al. [51].
Integrated production and maintenance planning	Bennour et al. [38], Brandolesse et al. [52], Cassady and Kutanoglu [53], Pandey et al. [54], Hadidi and Al-Turki [55], F. Hnaïen et al.[56], Sortrakul et al. [57].
One machine	Restrepo et al. [58], Wang et al. [59], Berthaut et al. [60], Cassady and Kuntanoglu [61], Cui et al. [62], Sortrakul and Cassady [63], Mehdi et al.[64], Yulan et al. [65], Lu et al. [66].
Parallel machines	Berrichi et al.[67], Nourelfath and Châtelet [68].
Integration of production plans, maintenance and quality	Nourelfath et al. [69], Gouiaa-Mtibaa et al. [70], Ben-Daya et al. [71], Ben-Daya et al. [72], Bouslah et al. [73], Colledani et al. [74], Pandey and Kulkarni [75].
Multi-machine	Bajestani et al.[4], Gharbi and Kenné [22].
Economic quantity of production (EPQ)	Abdulnour et al. [76], Groenevelt et al. [77], Makis and Fung [78], Chung et al. [79], Ben-Daya et al. [72], Wang and Sheu [80], Budai et al. [81].

The third category concerned models with the objective of jointly determining the optimum size of a buffer stock and the optimal age of preventive maintenance. The authors of [44] proposed an analytical model to study the effect of the adopted preventive maintenance policy and the age of the equipment on the buffer stock levels. In addition, reference [82] also developed a mathematical model to find the optimal torque (buffer stock and preventive maintenance age) that minimised the average total cost per unit of time. In the same way, the authors of [42] presented a common optimisation between the age of preventive maintenance and the control stock in a production line consisting of  $n$  machines. In developing an analytical model, the objective was to determine both the size of the buffer stock and the preventive maintenance period for an unreliable production unit that was subject to regular preventive maintenance of a random duration [83].

The last category dealt with the integration of three axes: production, maintenance and quality. In addition, the model integrating production, maintenance and process quality has been the subject of research [84]. The safety stock construction conditions based on the economic order quantity, denoted MEQ (Economic Manufacturing Quantity) were studied by [85]. Recently, the authors of [69] proposed a joint selection model for the optimal values of the production plan and maintenance policy, while taking into account the quality costs for an imperfect process. In the same vein, reference [73] addressed the joint optimisation of production, preventive maintenance and quality control using acceptance sampling plans, proposing a holistic

approach to joint optimisation of production lot size, safety stock, acceptance sampling plan and revision schedule, considering a quality constraint for the degradation of production systems. In addition, the authors of [86] revised the methods and tools to support the strong interaction between production logistics, quality and maintenance functions. They also showed that performance improvement was achieved in relation to existing solutions, which dealt only with the aspects of quality. Table 2 focuses on the various approaches to integrated production maintenance that were developed between 1995 and 2016. Some authors positioned themselves at the level of optimisation of production and the policy of preventive maintenance, or the integrated planning of production and maintenance, by treating as an example the case of a single machine or parallel machines.

### ***Industrial Subcontracting***

The concept of outsourcing (or externalisation) has helped organisations reduce operating costs. Subcontracting is defined as the supply of goods or services according to the contractor's design and specifications [87]. Companies often outsource to organisations that possess complementary skills. In fact, the increasing use of subcontracting is a major structural change in the organisation of enterprises. French Law n° 75-1334 of 31<sup>st</sup> December 1975 on subcontracting defines subcontracting as the operation by which an entrepreneur (contractor) entrusts a subcontractor under his responsibility to another person called under -processing the performance of all or part of the contract of undertaking or part of the public contract concluded with the contracting authority. The subcontractor subcontracts the contractor while at work by supporting a part of the industrial risks generated by his work. Similarly, it is subordinated to the directives of the client who will be precise and elaborate, the minimum being the specifications [88]. Outsourcing has expanded in the industrial world in virtually all areas [89]. Outsourcing allows companies to react flexibly to market demands, to acquire the skills and professionalism that they do not have, to tighten their investment and hence their internal resources around their core business [90]. Other authors [91] have justified the use of subcontracting by insufficient internal technology to efficiently produce a product or the impossibility of producing the quantities requested within the specified time. In addition, outsourcing is a solution that allows companies to benefit from the complementary skills of external organisations. They also modelled the interaction between the employees of the "host" company and the outsourcing company. Moreover, subcontracting is considered by many industrialists as a necessity, the extent of which has been widely emphasised [31, 92]. It therefore represents not only an increasing share of activities, but has also become almost indispensable. The volume of outsourced hours has steadily increased and may represent a strong proposal for the number of hours worked [93].

### ***Different Types of Subcontracting***

Subcontracting can be described in three ways, depending on the point of view adopted: the means required for operations, the location of operations or the degree of subcontracting. Each of these three axes determines two categories of subcontracting:

- Subcontracting of capacity and subcontracting of specialty if one focuses on the means. The subcontracting of capacity constitutes a reinforcement of the activity; the user company itself is able to carry out a part of this activity [94]. On the other hand, specialty subcontracting refers to the taking over by a subcontractor of highly specialised activities in which the ordering firm does not provide at most [95].

- Internal subcontracting and external subcontracting if reference is made to the location. For internal subcontracting, it consists of a so-called "user" company, entrusting work to an outside company [93] on its own site and during its own activity. Outsourcing is particularly relevant to the automotive industry and telephone information [96].
- Subcontracting in cascade and subcontracting to a single rank according to the degree of subcontracting, when a user undertaking entrusts one or more operations to an outside undertaking under a contract of enterprise, the level 1 subcontracting undertaking entrusts in its turn all or part of the operations which have been entrusted to it to a third company. The latter then becomes a subcontractor company at level 2. This type of subcontracting frequently allows meeting demands for flexibility and increases responsiveness of companies. An increase can be seen in the rate of temporary employees and fixed-term contracts among subcontractors of rank 2 and above [93, 95].

### ***Motivations of Subcontracting***

Outsourcing is not always justified by production costs. It is part of the logic of cooperation and coordination based, for example, on technological motivations, to satisfy the customers' needs in terms of time and quantity [97-99]. Sometimes, companies turn to external sources and collaborate with external partners to develop shared technological capabilities [100, 101]. The motivations that can lead a company to outsource part of its activities and trust a provider to achieve them can be summarised as follows:

**Financial motivation:** the financial aspect is one of the first reasons given in the literature, in line with the desire to reduce costs internally. Specialised firms have been able to rationalise their costs and offer services that enable the client to achieve productivity savings, even if internal resources exist [102, 103].

- i) **Strategic motivation:** the user company selects the investments that appear to be the most creative in value [91]. In this case, it may decide to abandon activities that have the least added value in relation to its core business [104].
- ii) **Skill-based motivation:** there are companies that are specialised in the outsourced activity and have competent staff, tools and materials needed to carry out the interventions [92, 104]. This is a specialty outsourcing.
- iii) **Social motivation:** reference [105] explained that subcontracting can be linked to a difficult social context and that it can be a means of circumventing the binding statutes of large order-giving companies.

### ***The Limits of Industrial Subcontracting***

The limits of outsourcing will be achieved when they impact the production tool. These limits may cause difficulty in retaining internal know-hows on sensitive equipment, even if complex operations are occasionally entrusted to specialists. In addition, there is a strong dependency to the subcontractor and lack of motivation for the subcontractor to improve the quality of the product [106].

### **The problematic of joint management of maintenance and production under constraint of subcontracting**

The main objective of the manufacturing company is to increase productivity, with the aim to satisfy the customer's needs. To acquire new markets, the company applies outsourcing, which involves entrusting a part of its production to a service provider. To guarantee a win-win situation, the company adopts a new strategy to manage production and maintenance in a joint way. The issue of joint management of maintenance and

production using subcontracting is addressed at several levels (Figure 4). First, the main concern of the ordering company is the choice of the most optimal subcontractor. This choice of subcontractor is based on several conditions, namely the cost of the minimum production, as well as the maximum availability of the subcontractor's equipment. Secondly, if the two companies are not generally located in the same geographical location, we are talking about offshoring. Therefore, the management of the maintenance of the two companies, the company ordering, and subcontracting remain ambiguous. Hence, the management of the maintenance and production of the subcontractor are not managed by the ordering company. The inefficiency and unavailability of the subcontractor's equipment will lead to costs of non-conformity of the manufactured products. For this reason, it is necessary to make a planning of the production actions for the ordering company at the level of determination of the quantity to be manufactured for the two companies, to respect the customer requirements in terms of time and quality.



Figure 4. The problems of joint management of maintenance and production under the constraint of subcontracting.

#### ***Integration approaches for maintenance and production using subcontracting***

The traditional approach that dissociates maintenance and production is not satisfactory in terms of time, cost and quality. The integration of joint management of maintenance and production has become necessary. The goal is to find an economical production plan, as well as an optimal maintenance strategy. When the demand exceeds the maximum production capacity, in such a situation where the company is obliged to satisfy a demand that exceeds its production limits to keep these customers, the latter uses subcontracting. Considering the preceding, the following questions arise. First, what is the basis of maintenance and production management for the contracting company and the subcontracting company? How can we balance production capacity constraints, customer demand and availability of equipment to achieve the most optimal result? How can the contracting company make an economic choice between several subcontractors? Here, the focus is not on theoretical applications, but on the joint management approaches for joint management of maintenance and production using subcontracting of existing systems.

Real and new strategies that consider the management of integrated maintenance under subcontracting constraints have been studied by [107] by providing a methodology for determining the level of the security stock and the storage capacity for multiple products of several manufacturing facilities with outsourcing options [107]. In this sense, reference [108] proposed a joint policy of joint production and subcontracting of

unreliable production systems, based on an approach that includes experimental design, variance analysis, response surface methodology and simulation modelling. [108] achieved a reduction in the total cost incurred up to 20%, compared to the results obtained by [107] when considering the customer satisfaction constraint. Other authors [109] have treated conditional maintenance for a production system that considered reliability aspects and environmental requirements to find the optimal inspection dates by considering the average cost of the cycle unit of time. To meet market demand, the manufacturer outsourced part of the demand to another entrepreneurial company. In the same context, a combinatorial approach to maintenance and production management in the case of outsourcing was developed by [110]. The objective of the work was to determine simultaneously for each period the optimal internal production as well as the rate of outsourcing. They used a genetic algorithm to optimise the total cost, including internal production, maintenance and shortage. In addition, reference [111] introduced environmental parameters in the analysis of the reliability of the equipment during its life cycle. These parameters considered human health, safety and the impact on the external environment.

Recently, a case study which proved the influence of the subcontractor's constraints on the optimal maintenance strategy adopted was presented in [112]. In their work, the authors of [113] developed and optimised a new maintenance policy while considering the constraints of subcontractors. They considered a production system represented by a machine producing a single type of product to satisfy a constant demand. The machine used the subcontracting represented by a second machine to complete the whole of the demand exceeding the maximum rate of the machine. Two preventive maintenance policies for the contractor machine were studied: the first did not consider the condition of the subcontracting machine, whereas the second did not. They showed that, under the given conditions, an improved maintenance policy could be achieved by providing the best age to perform preventive maintenance based on the history of the main machine and the subcontracting machine condition. Following these results, the authors of [114] have pursued the same context to deal with the same problem, but with two subcontractors differing in unit cost of production and availability. Initially, they proposed a strategy based on only one of the two subcontractors. They proved that the criteria for selecting the best subcontractor only concerned the unit cost of the lost demand. In the second step, they defined a policy of switching between the two subcontractors, starting with the least reliable and the cheapest, then switching to the other. The optimisation of this strategy was sequential. The first step was to determine the optimal age for preventive maintenance by minimising the average maintenance cost and then calculating the optimum switching date during the maintenance period by minimising production and shortage costs. In addition, other authors [115] have addressed a manufacturing problem for a production system that considered the return of the finished product. The aim was to establish an optimal production and maintenance plan while considering the production rate and the failure rate of the machine. In addition, reference [116] developed and optimised a new maintenance policy integrating the constraints of the subcontractor. They dealt with a case study that demonstrated the influence of the subcontractor's constraints on the optimal maintenance strategy adopted. Based on the results obtained, reference [117] also analysed the combined production and maintenance policies of a manufacturing system subjected to a subcontracting constraint. They studied analytically the problem of the integration of the subcontracting activity and the number of subcontracting tasks to be carried out during a maintenance cycle. They have assumed that production was governed by a common policy of maintenance

management and production control. They were interested in the problem of unforeseen extensions in the duration of subcontracting. According to [117], the integration of maintenance into subcontracting production is a trade-off between production management and maintenance management and managing the production support in which several subcontracting companies differ by their availability and unit production costs. Also, reference [118] proposed a different optimal plan combined with a preventive maintenance policy aimed at reducing machine degradation while minimising the total cost including production, inventory and maintenance costs. They also proposed a model that simultaneously optimised a production plan and a maintenance policy by trying to find the optimum times for carrying out preventive maintenance actions and by defining the transferable quantity of the contractor's machine to its subcontractor counterparty. Concerning the determination of the optimal age  $T$  and the optimal stock, reference [119] put forward an analytical model in the context of a production system with an outsourcing option. This model allowed simultaneous determination of  $T$  and  $S$ , minimising the average total cost including the cost of production, maintenance, lost orders and storage. Similarly, the authors of reference [120] studied a manufacturing system that used subcontracting to satisfy a random demand over a finite horizon. The aim was to find an optimal production plan that took account of subcontracting. Subsequently, reference [6] used outsourcing as an independent production system to meet a random demand. On the other hand, it considered a realistic case; the subcontractor can provide only a fixed amount throughout the horizon, by determining an optimal production plan considering the degradation of the machine and simultaneously minimising inventory, degradation and cost of production.

For their part, an analytical model has been proposed by [121] to optimise maintenance and production in a subcontracting context by integrating a stock to compensate for losses due to the unavailability of the ordering machine and the subcontractor. Recently, reference [122] proposed an integrated model that defined the structure of a common optimal policy for the interaction of production, quality, maintenance and subcontracting activities in a context of deterioration. Another model of subcontracting was presented by [7], which obtained an optimal production plan and a preventive maintenance program, the aim being to reduce the frequency of failure. Non-compliant products returned by customers were sent to a subcontractor for recycling to restore them in good condition. A work by [123] focused on combined production and maintenance plans for a manufacturing system, satisfying a random demand over a finite horizon. In their model, they assumed that the failure rate depended on time and production rate. Furthermore, the authors of reference [124] treated the adjustable capacity for an unreliable manufacturing system in which a standby machine was required to serve as a support to satisfy product demand if the inventory level fell below a specific threshold.

Recently, the authors of reference [125] worked in the context of prediction problems with a subcontracting constraint. The objective was to determine the production plans for the main machine, as well as for the subcontractor machine. The purpose was to determine the exact time for carrying out preventive maintenance actions, history and production plan of the main machine, as well as the condition of the subcontractor machine. They developed two maintenance strategies: SMS (Simple Maintenance Strategy) and IMS (An Improved Maintenance Strategy) to increase the availability of the main machine and reduce maintenance costs. In another context, reference [126] addressed the problem of predicting production optimisation and maintenance under subcontracting constraint with transport delay. They proposed an analytical formulation of this problem to find an optimal production and maintenance

plan. They determined an effective periodic preventive maintenance policy with minimum repair and an optimal production plan that integrated the various constraints for production rates, transport time and return deadline. Their proposed maintenance strategy was carried out to minimise the total maintenance cost to obtain the optimum number of preventive maintenance actions. Other authors [127] have addressed the problem of a dynamic cellular manufacturing system under dynamic environmental constraint and developed an integrated mathematical model of multi-period cell formation and production planning. The aim of the analytical analysis was to minimise the cost of reconfiguration, partial subcontracting, intra/cellular transfer and inventory by showing the impact of the compromise between production costs and outsourcing costs. Table 5 summarises some of the integrated maintenance models under subcontracting constraints, based on the study system, the decision parameters, the objective function and the method of resolution presented in the next section.

### Resolution Approaches

The goal of an optimisation problem is to obtain the best result under the given circumstances. Optimisation consists of determining the extremums of a function, called the objective function in literature. The latter corresponds to an algebraic relation between one or more output variables of the studied system, called 'criteria'. The success of the optimisation procedure depends on the choice of the objective function and its functional relationship with the control parameters [128].

Certainly, the optimisation of the maintenance strategies consists of finding the optimal dates of preventive maintenance interventions while respecting the fixed objectives. In addition, to reduce production costs, planning tools and techniques should be adopted to align resources with demand and to optimise production capacity in line with the current business realities. To optimise the maintenance and the production in a simultaneous way, it is rather necessary to go towards a coupled algorithmic approach. The goal of an optimisation algorithm is to find a solution of a highly complex problem automatically and quickly. In this sense, several methods of resolution were developed. These methods can be summarised into two main families:

- **The exact methods** (complete) that guarantee a unique optimal solution. They provide optimum solutions for problems of reasonable size.
- **The approach methods** (incomplete) that lose completeness to improve efficiency. They are a very interesting alternative for dealing with large optimisation problems if optimality is not paramount. Figure 5 shows the set of algorithms used for optimisation to solve optimisation problems.

An integrated maintenance optimisation model is a mathematical model in which the costs and benefits of maintenance and production are quantified to achieve an optimal balance between both. Definitely, the methods of resolution and optimisation have been used more and more for a long time where taboo search methods and genetic algorithms can be cited [129-131]. Over the past decade, significant progress has been made with the emergence of a new generation of powerful and general approaches, often called meta-heuristics [132, 133]. Several approaches have been developed to solve the problem of planning and maintenance of joint production. Moreover, some mathematical propositions and properties have been suggested and applied in the proposed heuristic to solve this integrated problem based on the Lagrangian relaxation of the capacity constraints and the optimisation of the sub-gradient [35]. In addition, heuristics based on genetic algorithms have been used to solve an integrated optimisation model for production scheduling and preventive maintenance planning [61]. The optimisation of

integrated maintenance is developed as a mathematical discipline in operational research. Hence, the choice of optimisation method impacts the decision-making regarding the strategy adopted.

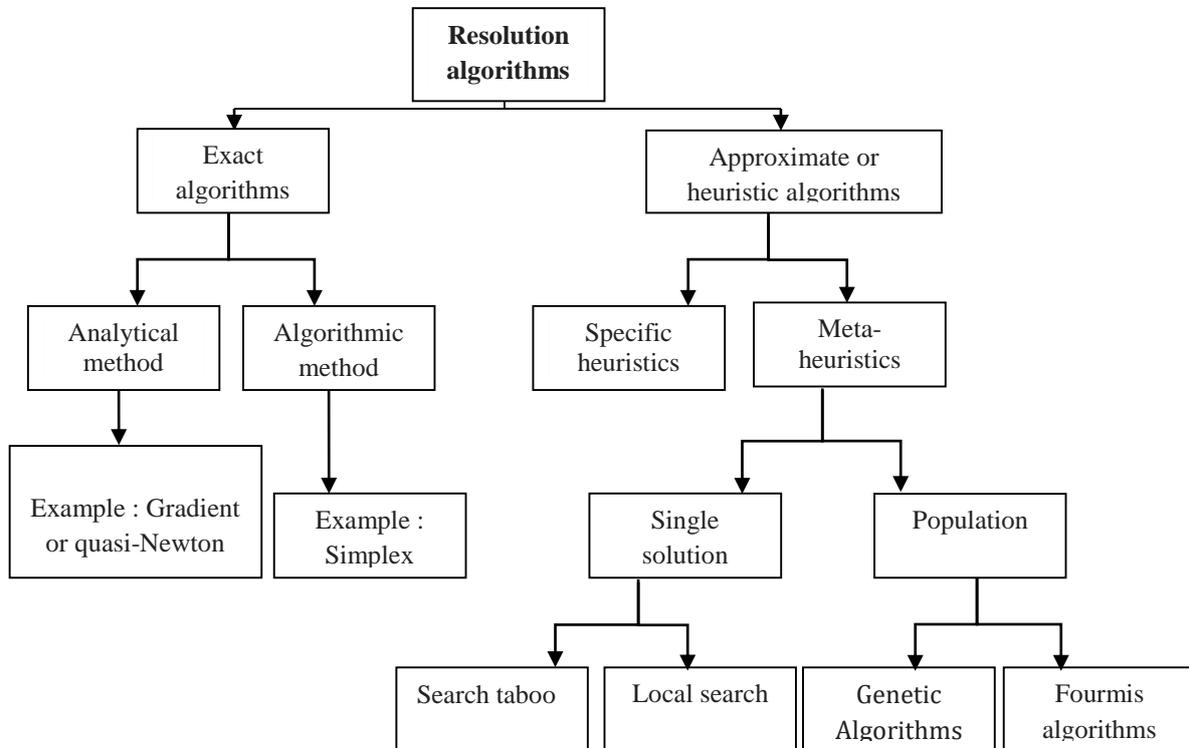


Figure 5. A classification of optimisation algorithms [134]

## RESULTS AND DISCUSSION

Some published references are definitely missing in this work. Secondly, for reasons of clarity, a terminology covering all the current ratings has been opted, making it possible to identify the decision-making parameters of the integrated maintenance for production using subcontracting (Table 3). These settings are necessary for integrated problem optimisation. The analysis of the table of synthesis of the models of maintenance integrated with production under subcontracting constraint (Table 5) has made it possible to affirm that in most cases, the system of study consisted of two types of machines: manufacturer main machine (M) and subcontractor machine (SM), concerning the differing decision parameters from one model to another. Generally, parameters and costs of maintenance/production of the manufacturer and those of the subcontractor were found. The objective function was frequently considered to be the total cost of the maintenance/production policy with the subcontracting constraint. These models made it possible to determine the stock level, the optimal age of preventive maintenance, the optimal production plan, and the choice of a subcontractor among several others based on different data.

In our research, we considered 24 references for integrated production maintenance using subcontracting of production systems, as well as the management of subcontracting production shown in Table 4. Figure 6 indicates the percentage of publication by the type of resolution method adopted. 58% of the references used the

analytical resolution while 25% of the publications adopted the exact/approximate methods to optimise the objective function. The remaining 17% of publications represented the other types of optimisation methods. Obtaining an exact solution for such a hard problem in a reasonable time is hardly attainable. Thus, it is necessary to use a heuristic or meta-heuristic approach to solve joint optimisation models for real-size problems. In general, the optimisation methods employed included Markov decision methods, linear and nonlinear programming, decision analysis techniques and heuristic approaches.

Table 3. Decision parameters for hybrid management maintenance/production under subcontracting constraint

Settings	Significations	Settings	Significations
$U_{max}$	Maximum production rate of a machine M	$C_h$	Unit cost of holding
$C_M$	Unit cost of production of a machine M	$C_s$	Unit cost of shortage
$C_{SM}$	Unit cost of production of a machine SM	$TD$	Delay in transport of urgent subcontracting
$P_M$	Production rate of M	$P_{SM}$	SM machine production rate
$T_{SM}$	Machine SM availability rate	$B$	Service level of the machine SM
$D$	Demand quantity	$T_V$	Inventory level
$F$	Fault failure rate of machine M	$C_p$	Preventive maintenance action cost
$C_{DM}$	Cost of degradation of machine M	$C_c$	Cost of Corrective Maintenance Action
$MTBF$	Mean time between failures	$N$	Number of preventive maintenance actions of machine M
$MTTR$	Mean time to repair	$T_p$	Average preventive maintenance action time of machine M
$U_{max SM}$	Maximum production rate of the subcontractor	$T_{CM}$	Average corrective maintenance action time of machine M
$U_{min SM}$	Minimum production rate of the subcontractor	$T_{cSM}$	Average corrective maintenance action time of machine SM

In general, the integrated works aimed at achieving an optimal maintenance strategy as well as an economical production plan by constructing a production plan that respects the dates of preventive maintenance intervention. In planning maintenance tasks, different planning policies can be implemented. Some authors proposed to perform maintenance tasks during the scheduled shutdowns of production machines by planning and determining a schedule of maintenance interventions and production operations in a joint manner. Others integrated maintenance into production, determining the optimal buffer size and age of preventive maintenance in a sequential way; beyond this, the coupling between production and maintenance at the management level.

Table 4. Synthesis of resolution approaches

Reference	Approach
[107]	Heuristic
[108]	Combined approach between experimental design, variance analysis, response surface methodology and simulation modelling.
[109]	Analytical study
[110]	Genetic algorithms
[112]	Analytical study
[113]	Analytical study
[114]	Analytical study
[116]	Analytical study
[117]	Analytical study
[117]	Analytical study
[118]	Analytical study
[119]	Analytical study
[120]	PA: Perturbation Analysis
[6]	FPA: Finite Perturbation Analysis
[121]	Analytical study
[122]	Dynamic programming
[7]	Stochastic quadratic linear optimisation
[123]	Analytical study
[124]	Dynamic programming
[125]	Analytical study
[126]	Analytical study
[135]	Analytical study
[136]	Genetic algorithms
[98]	Heuristic

One study has chosen to deal with the third axis of quality concerning the models of the maintenance integrated to the production under the constraint of subcontracting. The main objective was to find a compromise between joint maintenance/production and subcontracting by optimising the total cost, since subcontracting of production made it possible to satisfy the customers' needs in terms of time and quantity. The disadvantage of these models was that they dealt with specific cases at the level of the study system, decision parameters and objective functions, which cannot be generalised and applied to other problems.

This review also suggests some avenues for future research. With the dominance of globalisation and the concept of open markets, most factories produce different types of products for different markets. The price of these products becomes a problem and must be linked to the cost of production, maintenance and quality. Logistics can be included in the integrated maintenance. Integrated models can also be studied for the subcontracting of maintenance alongside the subcontracting of production. Therefore, it is necessary to make a change in the company's culture regarding the management of maintenance and production in a joint by adopting outsourcing as a solution that satisfies the customer's need in terms of quantity and time. Hence, slandering modern tools for managing maintenance integrated with production using subcontracting is important.

Table 5. Synthesis of integrated maintenance models for subcontracting production.

Reference	Settings	Objective function	Achievements	Method of resolution
[114]	$C_c, C_p, C_{SM}, C_M, C_s, T_{SM}, F$	Average total cost including maintenance, production and loss of demand.	-Choice of a subcontractor between several subcontractors. -Optimal date for preventive maintenance machine M. - Switching strategy between subcontractors.	Analytical resolution
[119]	$C_c, C_p, C_{SM}, C_M, U_{max}, B, C_s, T_{SM}, T_V$	Average total cost per unit of time, regrouping preventive maintenance actions, production, inventory and degradation of the machine M.	-Determining an optimal production plan. -Determine the optimal stock level. -The quantity to be subcontracted. -Optimal Age of Preventive Maintenance.	Analytical resolution
[6]	$B, F, C_{SM}, C_M, T_{SM}, U_{max}, P_M, P_{SM}, U_{minSM}$	-Number of preventive maintenance action. -Cost production according to availability.	-Determine a production plan. -The optimum production rate of the two manufacturing systems of machines M and SM. -The number of preventive maintenance actions of the machine M.	FPA: Finite Perturbation Analysis
[124]	$U_{max}, P_M, P_{SM}, C_c, C_p, C_{SM}, C_M, C_{DM}$	-Total production cost. -Total maintenance cost.	-Establish an optimal production plan. -Establish an optimal maintenance plan minimising the total cost of maintenance	Analytical resolution
[108]	$T_V, P_M, P_{SM}, U_{max}, MTBF, MTTR, C_{SM}, C_M, TD$	The total cost incurred while respecting the constraints of the client.	Determine optimal control parameter values that minimise the total cost incurred.	Combined approach between experimental design, variance analysis, response surface methodology and simulation modelling.
[135]	$C_p, C_c, C_{pu}, U_{max}, d, T_p, T_{cM}, T_{cSM}$	The total average cost of the maintenance/production policy.	-Determine the optimal age of preventive maintenance. -Determine optimal stock level and total maintenance cost	Analytical resolution
[110]	$T_V, C_h, C_s, C_p, C_c, P_{SM}, U_{minSM}, U_{maxSM}$	The total estimated cost includes the costs of production, holding, maintenance, shortage and subcontracting.	-Determining optimal internal production. - Subcontracting rates.	Genetic algorithms

Our future work aims to develop new integrated maintenance-production models in the context of outsourcing by offering manufacturers new strategies through which it

would be possible for them to simultaneously process the parameters of production and those of maintenance in accordance with customer requirements. Moreover, we plan in the next work to add the constraints related to the cost of quality by using an analytical resolution. The model will be simulated later in order to evaluate its effectiveness.

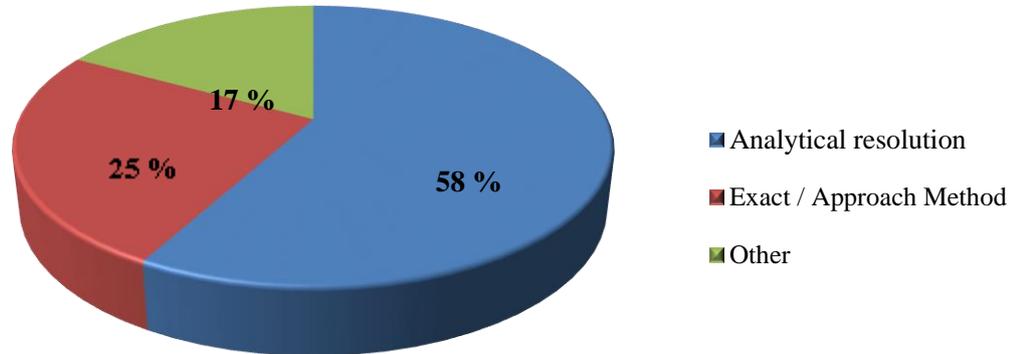


Figure 6. Percentage of publication by type of resolution method adopted.

## CONCLUSIONS

This article highlights the integrated maintenance of a production system with the objective of satisfying customer demand that is higher than its maximum production capacity by using outsourcing. Initially, the integrated maintenance/production models were presented by outlining the approaches adopted. Then, the models of integrated maintenance under subcontracting constraint were synthesised using the system studied, the decision parameters, the objective function and the set of optimisations used. This work analysed more than 100 references related to maintenance management integrated into the production system with a subcontracting constraint in relevant operational research and management reviews. To study the work analysed, a classification was proposed based on the analysis of the following aspects: separate management, integrated management, subcontracting constraints, modelling approach, optimisation approach, development tool, limits and benefits.

Finally, the interaction between modelling and algorithms will play an important role in future research. The inclusion of industrial concerns leads to larger and more complex models and therefore more complex algorithms are needed to solve them. Solution approaches for integrated models will be based on previous research and on separate models. In this perspective, on the one hand, our research will lead us to find a compromise between the maintenance management and the production management, and on the other hand, the subcontracting services offered by the company, guaranteeing firstly the internal stability of the company and the evolution of its profits while proposing the implementation of feasible models and tools capable of prescribing the best maintenance policy in the case of production under the constraint of subcontracting.

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