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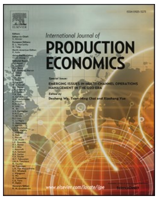

# The value of integrated planning for production, inventory, and routing decisions: A systematic review and meta-analysis

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ABSTRACT

This paper presents a comparison of sequential and integrated planning for the production routing problem, in which production, inventory, and routing decisions must be made. The aim is to estimate the expected value of treating the problems as a whole, rather than making decisions sequentially. In particular, the following research questions are posed: What is the expected cost reduction when combining production, inventory, and routing in a single modeling framework, compared to solving the problems individually in a sequence? Under which circumstances is it most beneficial to tackle an integrated problem? In other words, the goal is to establish whether the solutions obtained by the integration are clearly better than approximate solutions obtained by a more simplified process, and if so, under which circumstances this difference is the most pronounced. To answer these research questions, a systematic review was performed, resulting in a set of 20 relevant articles that were analyzed in depth. For the first research question, computational results from 15 articles were obtained and analyzed through a meta-analysis. The analysis estimated an expected cost savings provided by integration of 11.08%, with a 95% confidence interval of [6.58%, 15.58%]. For the second research question, individual results obtained via sensitivity analyses in 20 relevant articles were summarized qualitatively, enabling insights into how the potential savings by integration is influenced by parameters such as the degrees of freedom, the cost, and the capacity.

## 1. Introduction

A typical supply chain consists of sequential operations of production, inventory, and distribution. Historically, the decisions have often been considered separately, but the amount of literature dealing with joint optimization of two or more of these aspects is growing. The integrated problems can bring economic advantages; however, solving integrated problems is usually much more challenging computationally, compared to the sequential solution (Laínez-Aguirre and Puigjaner, 2015) of simpler, classical or hierarchical problems (Absi et al., 2018). Solving the problems independently, even by means of exact methods, leads to a suboptimal solution for the integrated problem, whereas the integrated problem itself can, for the most part, only be solved heuristically (Speranza, 2018).

The advances in decision support tools and scientific research have brought a trend leading to the optimization of ever more integrated parts of the logistics system (Archetti and Speranza, 2016). The production and distribution decisions are mutually related problems. It has been claimed that the combination of all of production, inventory, and distribution or routing decisions in supply chains offers tremendous cost saving opportunities to firms (Solyali and Süral, 2017). Although the integration of the decisions allows for better solutions, quantifying the improvements is extremely important since integrated approaches imply a higher degree of organizational and computational complexity (Fahimnia et al., 2013). However, a limited amount of research has been done so far on assessing the value of integration (Moons et al., 2017), and the evidence for the benefits of integration is scattered and incomplete. Therefore, studies evaluating the benefits of integrated policies are still important contributions to the research literature.

This paper attempts to answer the following main question: How much cost savings can one expect by solving an integrated problem, rather than a series of sequential problems consisting of production decisions, inventory decisions, and routing or distribution decisions, respectively? This is particularly interesting when faced with a complex supply chain where a series of optimization problems may be solved sequentially using exact methods, whereas an alternative formulation as

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an integrated problem may be prohibitively time-consuming to solve to optimality. Knowing the expected savings from solving the integrated problem can then provide an indication of whether a heuristic solution to the integrated problem, perhaps with a gap to a known dual bound, will lead to better decisions. While inventory routing problems, where no production decisions are considered, also involve an integration of inventory decisions and routing decisions, we are in this paper only considering situations with three distinct types of decisions, including production, inventory, and distribution.

The problem of optimally coordinating production, inventory, and delivery operations is called the production, inventory and distribution routing problem (PIDRP) (Bard and Nananukul, 2009b; Lei et al., 2006), alternatively the production-inventory routing problem (PIRP) (Adulyasak et al., 2014a; Bard and Nananukul, 2010) or the production routing problem (PRP) (Absi et al., 2018). An integrated supply chain operational planning system is a tool that is used to jointly optimize several planning decisions, thereby capturing the additional benefits of coordination between sequential activities in the chain (Adulyasak et al., 2015b). A vendor-managed inventory system, in which the supplier monitors the inventory at retailers and also decides on the replenishment policy for each retailer, is a good example of such integration (Adulyasak et al., 2015b; Bard and Nananukul, 2009b).

The first study on the value of coordinating production and distribution decisions was provided by Chandra and Fisher (1994). A number of studies followed in the next decades, dealing with various formulations of the PRP (Golsefidi and Jokar, 2020). Most researchers focused on the development of heuristic methods such as adaptive large neighborhood search (Adulyasak et al., 2014b), hybrid heuristics (Archetti et al., 2011; Bard and Nananukul, 2009a), tabu search (Armentano et al., 2011; Bard and Nananukul, 2009b), greedy randomized adaptive search procedures (Boudia et al., 2007b), memetic algorithms (Boudia and Prins, 2009), two-phase iterative methods (Absi et al., 2014, 2018), particle swarm optimization (Chan et al., 2020), or mathematical programming-based heuristics (Avci and Yildiz, 2020), or on the development of exact methods such as variants of the branch and cut algorithm (Adulyasak et al., 2014a, 2015a; Archetti et al., 2011), branch and price (Bard and Nananukul, 2009a, 2010), or Lagrangian relaxation (Fumero and Vercellis, 1999). Extensive reviews have been written on formulations and solution methods for the PRP (Adulyasak et al., 2015b; Ruokokoski et al., 2010).

Some studies exist that explicitly evaluate the benefits of the coordinated approach. These tend to focus on a narrow set of test instances or problem types and often emphasize the development of novel solution methods rather than the evaluation of solving an integrated problem. While each of these studies provides some information on the benefit of integration in some specific setting, their individual results are sometimes conflicting, and one can not readily extract a true representation of the expected cost savings that potentially arise from the integration. Furthermore, many contributions to the literature consider only an integrated version, without comparing to a sequential approach. This is done despite the fact that, until now, there have been no attempts at presenting an overall estimate for the potential cost savings associated with solving an integrated problem. Such an overall estimate may thus provide useful information for researchers and practitioners that consider solving integrated problems.

The remainder of this paper is organized as follows. Section 2 provides the research method including the research questions, the references collection methodology used for our systematic review (meta-analysis), the study selection procedure, and the study quality assessment. Then, Section 3 presents an analysis and a unification of the results found through the systematic review. Section 4 provides a quantitative as well as qualitative analysis of the related data that were collected, while Section 5 contains the concluding remarks.

## 2. Methodology

A systematic review is a process of assessment and interpretation of all available research related to a research question or subject of interest (Afzal et al., 2009), while a meta-analysis is a statistical analysis combining existing results in the literature to obtain a more robust conclusion. Turkeš et al. (2020, 2021) provided an introduction to the methodology in a setting related to operations research, while Borenstein et al. (2009) and Higgins and Green (2008) provide more general and detailed material.

To examine the evidence of advantages and disadvantages of integrated PIRP comparing to the sequential, the following research questions are defined:

- RQ1: What is the potential cost savings when combining production, inventory, and routing in a single modeling framework?
- RQ2: Under which circumstances is it particularly beneficial to tackle an integrated problem?

Rather than setting up and executing a new set of experiments, a systematic review aims to answer the research questions by systematically appraising the evidence already present in the scientific literature. The output of the systematic review is thus either an answer to the research questions, or a realization that the current body of literature does not contain enough information to properly answer the research questions. The search for existing literature must be reproducible and transparent, and details of our search are given in Section 2.1. The literature identified must then be inspected, and relevant studies selected, according to a set of a priori well-defined criteria, as seen in Section 2.2.

To answer the research questions, the relevant studies are those that explicitly compare an integrated and a sequential approach for solving an optimization problem involving production, inventory, and distribution decisions. When performing a meta-analysis, the data from relevant studies are extracted and analyzed using statistical methods. The particular choice of statistical model may vary between meta-analyses. In our case, we consider the object of study to be instances of certain types of optimization problems. In particular, we aim to evaluate variants of the PRP and the instances of those problems when solved both as an integrated problem and as two or more sequential problems. The research literature contains a sample of such problems and instances, for which a comparison of integrated and sequential methods have been made. This leads us to use a random-effects model (Turkeš et al., 2020) to answer the first research question, while the second research question is not addressed through a meta-analysis, but in a more qualitative analysis.

When applying the systematic review and the meta-analysis we differentiate between a paper and a study. Considering our research question, we define a study as a comparison between an integrated and a sequential method as applied to a well-defined production routing problem and evaluated on a set of test instances. The comparison should be based on the best available solutions to each instance for both the integrated and the sequential methods. Given the structure of the body of literature, this means that there will be cases where a single study is presented in several different papers, for example if the best results to different instances are found by different solution methods presented in different papers. There can also be cases where a single paper contributes to more than one study, for example by testing solution methods on different versions of the production routing problem.

### 2.1. Search strategy

The search for relevant papers which consider optimization problems involving production, inventory, and routing decisions and, especially, a comparison of integrated and sequential approaches, was performed using the Web of Science (WoS) and the Scopus databases.

We used the following approach for minimizing the threat of missing relevant studies (Afzal and Torkar, 2011):

1. Summarizing the research questions into set phrases, keywords, and multiple criteria.
2. Identifying alternative words and synonyms for each criterion.
3. Using the Boolean `OR` to join alternate words and synonyms and `AND` to join major terms.
4. Performing a detailed analysis and study of the references identified.

The following search criteria were applied to the topic field of the web search engines:

- (production `AND` routing `AND` distribut*)
- `AND` (integr* `OR` coordinat*)
- `AND` [(compar* `AND` sequent*) `OR` (value)].

The asterisks can be replaced by any sequence of letters not containing space, so that for example "integr*" means that the matched string can contain any word starting with "integr" (i.e., "integration" or "integrated"). We restricted the search to articles and conference papers written in English, to avoid other documents indexed by the databases.

### 2.2. *Study selection procedure*

The selection procedure was divided into four phases according to the PRISMA guidelines (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) (Moher et al., 2009). The first phase involves searching for and identifying potentially relevant studies. The second and third phase investigates each of the identified studies to determine whether they are relevant for answering the research question. The last phase then summarizes the final set of studies to be included.

#### 2.2.1. *Identification & screening*

In the first phase of the search strategy, the search strings were applied using the two aforementioned databases. We applied the strings to a search within titles, abstracts, and keywords. Finally, we joined the results from the two separate databases and removed duplicates. The search in phase one was made on November 1st, 2019, and resulted in 52 papers being identified.

The second phase was split into two parts.

1. First, the 52 papers found in the previous phase were screened. Based on title of the paper, its abstract and keywords, studies that clearly did not relate to logistics, transportation, or supply chain management were removed. This included papers that were returned by the database searches but that were nevertheless obviously irrelevant. Here, 23 articles were excluded and thus 29 articles were retained for a further full review.
2. Second, a manual search through literature reviews and references in these 29 articles was made, as well as a manual search through lists of publications by the authors of papers from the previous part. Moreover, papers that cited any of these promising references were also screened. Finally, e-mail or face-to-face communication with some authors of promising papers was performed with the intention of identifying other relevant studies. This resulted in 40 additional articles being included for the full review process. Therefore, this phase has led to the selection of 69 articles for a full review in the next phase.

#### 2.2.2. *Eligibility*

During the review (eligibility assessment), a set of inclusion criteria were applied. The next phase includes studies that:

- combine production, inventory, and routing decisions in a single modeling framework;
- include both integrated and sequential approaches and their comparison, respectively.

These criteria were delineated further as borderline cases were encountered, leading to the following specifications:

- contributions with direct deliveries (or some form of network flow) are included as far as the distribution problem is of a combinatorial nature (not just solved in polynomial time);
- it suffices to have inventory limits at either the producer or the consumer, or else the holding costs must be non-negligible;
- if the holding cost is zero, there must be costs associated to setups and to transportation;
- any such problems including additional decisions (e.g., regarding facility location) are still acceptable.

Furthermore, we require that the sequential approach is truly sequential: all decisions regarding production are made first, followed by decisions regarding inventory and then distribution. In some cases, two of the three types of decisions could be made simultaneously, but we exclude situations where a method is going back and forth between different types of decisions.

Finally, we exclude technical reports that have not been published (to the best of our knowledge) after more than 10 years since their results were determined and reported (e.g., Ertogral et al. (1998)). This criterion led to 20 articles being retained as relevant for our review, and thus being included in the next phase.

From the 20 remaining articles, we attempted to collect data regarding numerical results on savings or benefits of integrated approaches compared to sequential approaches. This was successful for 15 of the articles. That is, the data were either included in the paper with no need for additional information or the data were sent to us by the authors of papers upon request.

#### 2.2.3. *Included*

The last phase (and the 15 papers, respectively) presents an input for the work described in sections 3 and 4. Fig. 1, which follows the PRISMA guidelines (Moher et al., 2009), provides a flowchart of the search and selection processes.

Table 1 lists the 48 articles that were excluded during the eligibility phase. The first part shows 21 articles identified in the database search, and the second part shows 27 additional articles found when examining

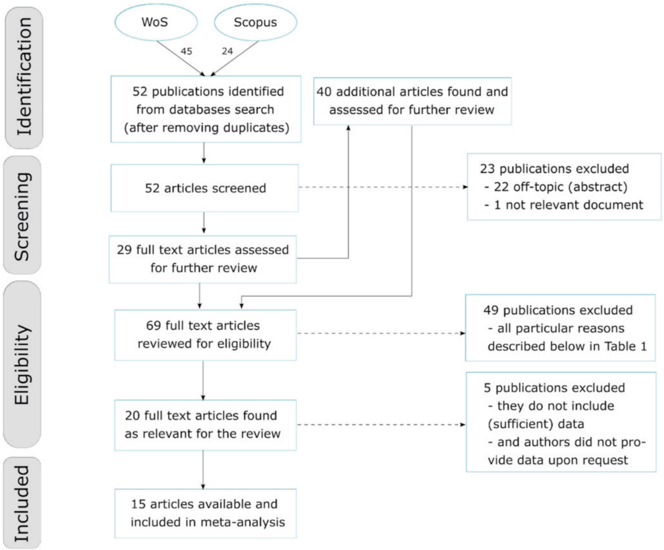


**Fig. 1.** PRISMA flowchart (Moher et al., 2009) of references collection methodology: identifications and selection of studies to be included in meta-analysis.

**Table 1**
Two phases of the screening part (from Screening to Eligibility): List of reviewed publications not relevant for the survey.

| Year | Authors (article) | PIRP | Int. | Seq. | Comp. | Exclusion explanation | Source/Found |
|---|---|---|---|---|---|---|---|
| 2005 | Chen and Vairaktarakis (2005) | × | ✓ | ✓ | ✓ | Neither inventory nor setup | WoS |
| 2005 | Bertazzi et al. (2005) | ✓ | × | ✓ | × | No integrated approach | WoS |
| 2005 | Erera et al. (2005) | × | – | – | – | No PIRP (a different problem) | WoS & Scopus |
| 2007 | Yin and Khoo (2007) | ✓ | × | ✓ | × | No integrated approach | Scopus |
| 2008 | Nagar and Jain (2008) | ✓ | ✓ | × | × | No sequential approach | WoS |
| 2013 | Low et al. (2013) | × | ✓ | × | × | No sequential approach, time minimzation | WoS |
| 2013 | Amorim et al. (2013) | × | ✓ | × | × | No sequential approach, no inventory cost nor limit | WoS & Scopus |
| 2013 | Sivakumar et al. (2013) | × | ✓ | × | × | No sequential approach, no production | Scopus |
| 2015 | Singh et al. (2015) | ✓ | × | ✓ | × | No integrated approach | WoS & Scopus |
| 2015 | Sawik (2015) | × | ✓ | × | × | No PIRP nor sequential approach | WoS |
| 2016 | Zamarripa et al. (2016) | ✓ | ✓ | × | × | No sequential approach | WoS |
| 2016 | Li et al. (2016) | ✓ | ✓ | × | × | No sequential approach | WoS |
| 2016 | Johar et al. (2016) | × | ✓ | ✓ | ✓ | No production nor inventory | WoS & Scopus |
| 2017 | Khalili et al. (2017) | ✓ | ✓ | × | × | No sequential approach | WoS |
| 2017 | Vahdani et al. (2017) | ✓ | ✓ | × | × | No sequential approach | WoS & Scopus |
| 2017 | Zhou and Peng (2017) | × | – | – | – | No PIRP (a different problem) | Scopus |
| 2018 | Dolgui et al. (2018) | ✓ | ✓ | × | × | No sequential approach | WoS |
| 2018 | Bourmand and Beheshtinia (2018) | × | ✓ | × | × | No sequential approach, no inventory cost nor limit | WoS |
| 2018 | Hu et al. (2018) | × | ✓ | ✓ | ✓ | No production decisions | WoS & Scopus |
| 2019 | Lin et al. (2019) | ✓ | ✓ | × | × | No sequential approach | WoS |
| 2019 | Karimi et al. (2019) | ✓ | ✓ | × | × | No sequential approach | WoS & Scopus |
| 1979 | Glover et al. (1979) | ✓ | × | × | × | No model nor computations | Cited by (Chandra and Fisher, 1994) |
| 1989 | Benjamin (1989) | × | ✓ | ✓ | ✓ | Linear network flow/transportation | Cited by (Sarmiento and Nagi, 1999) |
| 1991 | Blumenfeld et al. (1991) | ✓ | ✓ | ✓ | ✓ | Only analytical results | Cited by (Chandra and Fisher, 1994) |
| 1992 | Hahm and Yano (1992) | ✓ | × | × | × | No computations | Additional search |
| 1995 | Hahm and Yano (1995) | × | ✓ | ✓ | ✓ | Lack of routing decisions | Cited by (Chen and Vairaktarakis, 2005) |
| 1998 | Ertogral et al. (1998) | ✓ | ✓ | ✓ | – | Unpublished technical report | Cited by (Boudia et al., 2007b) |
| 1999 | Sarmiento and Nagi (1999) | ✓ | × | × | × | Survey, no model nor computations | Cited by (Darvish and Coelho, 2018; Chen and Vairaktarakis, 2005) |
| 1999 | Barbarosoğlu and Özgür (1999) | ✓ | ✓ | × | × | No sequential approach | Cited by (Darvish and Coelho, 2018) |
| 2001 | Brown et al. (2001) | ✓ | × | × | × | No model nor computations | Cited by (Darvish and Coelho, 2018) |
| 2001 | Jayaraman and Pirkul (2001) | ✓ | ✓ | × | × | No sequential approach | Cited by (Darvish and Coelho, 2018) |
| 2004 | Jolayemi and Olorunniwo (2004) | ✓ | ✓ | × | × | No sequential approach | Cited by (Darvish and Coelho, 2018) |
| 2005 | Pundoor and Chen (2005) | × | ✓ | ✓ | ✓ | Minimizes tardiness and transportation costs | Cited by (Johar et al., 2016; Toptal et al., 2014) |
| 2006 | Lei et al. (2006) | ✓ | ✓ | × | × | No sequential approach | Cited by (Toptal et al., 2014) |
| 2006 | Dawande et al. (2006) | × | ✓ | ✓ | ✓ | Lack of routing decisions | Cited by (Toptal et al., 2014) |
| 2010 | Bard and Nananukul (2010) | ✓ | ✓ | × | × | No sequential approach to compare | Cited by (Vahdani et al., 2017; Toptal et al., 2014) |
| 2010 | Zhao et al. (2010) | × | ✓ | × | × | No sequential approach nor production decision | Cited by (Absi et al., 2018) |
| 2010 | Chen (2010) | × | × | × | × | Survey, no model nor computations | Cited by (Darvish and Coelho, 2018; Johar et al., 2016) |
| 2011 | Sharkey et al. (2011) | × | ✓ | ✓ | ✓ | No distribution costs, lack of routing | Cited by (Darvish and Coelho, 2018) |
| 2013 | Ulrich (2013) | × | ✓ | ✓ | ✓ | Minimizes tardiness, no inventory | Cited by (Johar et al., 2016) |
| 2013 | Cóccola et al. (2013) | × | ✓ | ✓ | ✓ | No inventory limit nor cost | Cited by (Johar et al., 2016) |
| 2014 | Kuhn and Liske (2014) | ✓ | ✓ | × | × | No sequential approach | Cited by (Hein and Almeder, 2016) |
| 2015 | Adulyasak et al. (2015b) | ✓ | × | × | × | Survey, no model nor computations | Cited by (Darvish and Coelho, 2018) |
| 2015 | De Matta et al. (2015) | ✓ | ✓ | × | × | No sequential approach | Cited by (Darvish and Coelho, 2018) |
| 2016 | Darvish et al. (2016) | ✓ | ✓ | × | × | No sequential approach | Cited by (Darvish and Coelho, 2018) |
| 2017 | Li et al. (2017) | ✓ | ✓ | × | × | No sequential approach | Additional search |
| 2017 | Moons et al. (2017) | ✓ | × | × | × | Survey, no model nor computations | Cited by (Du et al., 2019) |
| 2018 | Darvish et al. (2019) | ✓ | ✓ | × | × | No sequential approach | Additional search |
| 2019 | Neves-Moreira et al. (2019) | ✓ | ✓ | × | ✓ | No pure sequential approach | Additional search |

*Note:* Columns: PIRP states if problem defined in each particular paper is relevant for our survey, approaches considered: Int. (integrated), Seq. (sequential), Comp. (their comparison).

citations and author's publication records, as explained in the rightmost column. A separate column is used to provide the reason for exclusion.

## 3. Analysis and synthesis of findings

Based on the review of 68 full text articles, and taking into account the selection criteria, 20 articles are included as relevant to evaluate the research questions. This section presents findings from the relevant papers selected for review, and highlights differences in the findings among various studies. Table 2 shows the journals in which the papers relevant for the review were published.

Table 3 provides a summary of the main problem characteristics and solution methods described and used in the selected literature references. Additional problem characteristics may influence the value of integration as well. We find that the demand is considered to be deterministic in all the included studies, and explicitly non-stationary only in two (Chandra, 1993; Chandra and Fisher, 1994), while the time between orders is considered fixed. Inventory is replenished dynamically in all the studies, with predefined periods where updates take place. Distribution is done using less-than-truckload transportation with explicit travel costs, while about half of the studies also considers a fixed cost for transportation. Production is considered as make-to-stock in all studies

**Table 2**
A summary of journals (and papers quantity, respectively) publishing relevant papers.

| Abbreviation | Papers | | | | Journal or Conference proceedings title |
|---|---|---|---|---|---|
| INFOR | Boudia et al. (2005a) | | | | INFOR: Information Systems and Operational Research |
| IJPE | Hein and Almeder (2016) | | | | International Journal of Production Economics |
| TechRep | Ruokokoski et al. (2010) | | | | Technical Report |
| IESM | Boudia et al. (2005a) | | | | International Conference on Industrial Engineering and Systems Management |
| MIC | Boudia et al. (2005b) | | | | Metaheuristics International Conference |
| ICSSM | Boudia et al. (2007a) | | | | International Conference on Service Systems and Service Management |
| IFAC | Boudia et al. (2006) | | | | IFAC Proceedings Volumes |
| CaCE | Marchetti et al. (2014) | | | | Computers and Chemical Engineering |
| JoS | Bard and Nananukul (2009b) | | | | Journal of Scheduling |
| PPaC | Boudia et al. (2008) | | | | Production Planning & Control |
| CaOR | Kuhn and Liske (2014) | | | | Computers & Operations Research |
| TransSci | Fumero and Vercellis (1999) | | | | Transportation Science |
| JORS | Chandra (1993) | Toptal et al. (2014) | | | Journal of the Operational Research Society |
| IJPR | Kuhn and Liske (2011) | Park (2005) | | | International Journal of Production Research |
| EJOR | Chandra and Fisher (1994) | Boudia and Prins (2009) | Darvish and Coelho (2018) | Absi et al. (2018) | European Journal of Operational Research |

except one, which considers make-to-order (Du et al., 2019).

Some of the papers by Boudia et al. do not include both an integrated and a sequential approach, but are nevertheless included since the results from the papers taken as a whole contain observations of both integrated and sequential approaches on the same set of problem instances. In the following, Section 3.1 discusses contributions studying a single product, Section 3.2 outlines contributions studying multiple products, and Section 3.3 presents contributions characterized by the inclusion of one or more additional decisions, such as location decisions or the supply of raw materials to the production facility. A synthesis of the numerical results available is given in Section 3.4.

### *3.1. Studies considering a single product*

Boudia et al. published a series of papers (see Table 3) that are linked to each other. In Boudia et al. (2005a) the authors developed a two-phase heuristic called H1 (also referred to as uncoupled or decoupled) to reflect the common practice of the industry to approach the production plan and the distribution plan separately. The first phase of H1 elaborates a production plan using Wagner and Whitin's method. The production plan is taken as fixed in the second phase, where trips are built for each day and a local search is applied day by day to improve them. This H1 was then compared with a three-phase heuristic, H2, where the third phase is a feedback on the production plan which determines definitive production dates for the quantities to be delivered. The comparison indicates significant cost savings. Then, Boudia et al. (2005b) implemented a greedy randomized adaptive search procedure (GRASP) as an integrated approach. These two papers and the included algorithms (H1, H2 and GRASP), were subsequently used for comparisons with various integrated approaches (Boudia et al., 2006, 2007a, 2007b, 2008; Boudia and Prins, 2009).

Boudia et al. (2007b) considered the aforementioned GRASP (Boudia et al., 2005b) and two improved variants (a reactive mechanism and a path-relinking process) starting with an initial solution based on the sequential approach. The study reported results on a per instance basis, reporting the percentage improvements of integrated vs. sequential planning. In total 90 instances were tested, divided in groups with 50, 100, and 200 customers, and the average savings relative to H1 were reported for H2 (9.1, 12.6, and 13.4%), GRASP (12.7, 17.8 and 17.3%), reactive GRASP (13.2, 17.8, and 18.4%), and GRASP with path relinking and two different strategies called S1 (13.4, 18.0, and 18.4%) and S2 (13.5, 18.0, and 18.3%). They concluded that the savings brought by integration increase with instance size.

Later, Boudia et al. (2008) extended their work from (Boudia et al., 2005a). Solutions are again computed by heuristics: two greedy heuristics followed by two local search procedures. The authors compared the uncoupled H1 approach with two variants of the iterative H2 approach. They used three sets of instances again (50, 100, and 200 customers) and for each of them provided 30 numerical results with average savings of 9.1–13.4% for the first variant of H2, H2/V1, and 11.2–15.2% for H2/V2. Boudia and Prins (2009) provided a contribution based on a memetic algorithm with population management (MA|PM) and compared it with the H1 and GRASP on the same instances as in (Boudia et al., 2007b). However, the reported savings by the MA|PM are clearly the most promising, with average cost savings in the range 23.0–25.8%. In some papers by Boudia et al. they considered a single product case (see Table 3); however, they used the case as a simplification and allowed its extension to the multiple product case without any restriction in the situation that the products are compatible and, e.g., can share the same storage place in the vehicles.

Again, for the same problem variant, Bard and Nananukul (2009b) proposed a reactive tabu search with path-relinking and compared it to the GRASP by Boudia et al. (2007a) reporting improvements ranging from 10–20% with respect to the best integrated results on the same instances.

Ruokokoski et al. (2010) solved the PRP using both integrated and sequential approaches; moreover, the integrated problem was solved with both heuristic as well as exact algorithms. The authors claim this paper is the first to make a comparison of integrated and sequential approaches based on optimal solutions. They provided a basic mixed integer linear programming formulation and several strong reformulations of the problem, and found that the total cost increases on average by 47% when employing an uncoordinated approach, which corresponds to 32% of savings when employing integrated approach. The integrated problems were solved to optimality within a 2-h time limit. If a heuristic algorithm was employed instead, the average CPU time was less than 1%, whereas the average cost increase compared to optimal solutions was only 0.33%.

**Table 3**
Selected papers (Phase 3): a summary of particular problems; sorted by additional decision inclusion (besides production, inventory and distribution) and number of products, respectively.

| Sec. | Article | Production | | | Inventory | | | Distribution | | | | | Add. dec. | Approach | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | $Set | #Plant | #Prod | $Hold | Site | Lim | $Trans | Pol | Fleet | #Vehs | Cap | | Seq | Int |
| 3.1 | Boudia et al. (2005a) | ✓ | S | S | ✓ | P,C | ✓ | ✓ | R | Hom | M | ✓ | × | H | H |
| | Boudia et al. (2005b) | ✓ | S | S | ✓ | P,C | ✓ | ✓ | R | Hom | M | ✓ | × | H | H |
| | Boudia et al. (2007b) | ✓ | S | S | ✓ | P,C | ✓ | ✓ | R | Hom | M | ✓ | × | H | H |
| | Boudia et al. (2008) | ✓ | S | S | ✓ | P,C | ✓ | ✓ | R | Hom | M | ✓ | × | H | H |
| | Bard and Nananukul (2009b) | ✓ | S | S | ✓ | P,C | ✓ | ✓ | R | Hom | M | ✓ | × | H | H |
| | Boudia and Prins (2009) | ✓ | S | S | ✓ | P,C | ✓ | ✓ | R | Hom | M | ✓ | × | H | H |
| | Ruokokoski et al. (2010) | ✓ | S | S | ✓ | P,C | × | ✓ | R | – | S | × | × | E | E/H |
| | Toptal et al. (2014) | × | S | S | ✓ | P | × | ✓ | DS | Het | M | ✓ | × | E | H |
| | Absi et al. (2018) | ✓ | S | S | ✓ | P,C | ✓ | ✓ | R | Hom | S/M | ×/✓ | × | E/H | H |
| 3.2 | Chandra (1993) | ✓ | S | M | ✓ | P,C | × | ✓ | R | Hom | M | ✓ | × | H | H |
| | Chandra and Fisher (1994) | ✓ | S | M | ✓ | C | × | ✓ | R | Hom | M | ✓ | × | E/H | H |
| | Fumero and Vercellis (1999) | ✓ | S | M | ✓ | P,C | × | ✓ | R | Hom | M | ✓ | × | H | H |
| | Park (2005) | ✓ | M | M | ✓ | P,C | ✓ | ✓ | DS | Hom | M | ✓ | × | H | H |
| | Boudia et al. (2006) | ✓ | S | M | ✓ | P,C | ✓ | ✓ | R | Hom | M | ✓ | × | H | H |
| | Boudia et al. (2007a) | ✓ | S | M | ✓ | P,C | ✓ | ✓ | R | Hom | M | ✓ | × | H | H |
| | Marchetti et al. (2014) | ✓ | S/M | M | × | P,C | ✓ | ✓ | DS/R | Het | M | ✓ | × | E | E* |
| | Du et al. (2019) | ✓ | S | M | ✓ | P | × | ✓ | R | Hom | M | ✓ | × | H | H |
| 3.3 | Kuhn and Liske (2011) | ✓ | S | M | ✓ | P | × | ✓ | R | Hom | M | ✓ | ✓ | H | H |
| | Hein and Almeder (2016) | ✓ | S | M | ✓ | P | × | ✓ | R | Hom | M | ✓ | ✓ | E | E* |
| | Darvish and Coelho (2018) | ✓ | M | M | ✓ | P,DC | × | ✓ | DS | – | M | × | ✓ | H | E/H |

*Note:* S-single, M-multiple; Set-setup, Prod-product; Hold - holding, C-customer, DC-distribution center, Lim-limit; R-routing, DS-direct shipment; Hom-homogeneous, Het-heterogeneous; Trans-transportation, Pol-policy, Vehs-vehicles, Cap-capacity; Add.dec.-additional decision; E-exact, H-heuristic; * with a specified gap.

The paper by Toptal et al. (2014) provides a comparison of three approaches: myopic, hierarchical, and coordinated. While the decisions are made jointly for the coordinated approach, for the myopic and hierarchical solutions, production planning decisions are made first, followed by outbound transportation decisions. More precisely, in the myopic solution, planning efforts for transportation are limited, made using a heuristic, and without giving explicit consideration to transportation costs and constraints. In the hierarchical solution, transportation planning is done in more detail in an effort to optimize the related costs. One by one, the average cost savings are: 10.1% for hierarchical over myopic, 10.0% for coordinated over hierarchical, and 18.9% for coordinated over myopic. The authors also concluded that the value of integration is particularly high when orders have large sizes, when inventory and vehicle holding costs are low, and when the availability of the lower cost vehicle shows high variability.

Absi et al. (2018) compared an integrated approach with two different sequential approaches: one in which production decisions are optimized first, and one in which distribution decisions are optimized first. Two different instance sets are employed: small instances with only one uncapacitated vehicle for distribution (which can be solved to optimality for the sequential approach) and larger instances with several capacitated vehicles (solved heuristically for the sequential approach). To solve the integrated problem, the authors applied a state-of-the-art heuristic algorithm for the PRP that was proposed earlier (Absi et al., 2014). The numerical results illustrate that the dominance of the integrated approach depends on the balance between production and distribution costs and on the balance between setup and inventory costs in production. Absi et al. (2018) found cases where a sequential approach achieves the best solution and situations where the integrated approach dominates both sequential approaches. More precisely, the value of integration increases when the production-distribution cost ratio increases while it decreases for an increasing setup-holding cost ratio. These two remarks mean that when the production-distribution cost ratio is low or the setup-holding cost ratio is high, it can be reasonable to use one of the two sequential approaches. However, the frequently observed high savings show that the decision about whether and when to adopt an integrated approach may otherwise have economic consequences.

### 3.2. *Studies considering multiple products*

One of the first papers that evaluated the benefits of integrated decisions was by Chandra (1993) in 1993. He considered a warehouse that needs to order goods which are then redistributed to end customers while considering inventories both at the customers and at the warehouse. The paper is included in this review by interpreting the warehouse as a production facility. Both sequential and integrated approaches were solved heuristically and applied to 33 randomly generated instances. It was shown that coordination of the production, inventory, and distribution decisions leads to a cost reduction in the range of 3–13%.

However, many refer to the paper by Chandra and Fisher (1994) from 1994 as the first paper on integration. As stated by Chandra and Fisher (1994), the integration of production and transportation planning decisions is a way to reduce costs and to increase efficiency in operations in industrial firms. In the paper, the objective is to minimize the total cost of production setups, transportation, and inventory at the retailer site. The authors compared two approaches: one in which the production scheduling and vehicle routing problems are solved separately, and another in which they are coordinated within a single model. In the decoupled formulation, the production scheduling is solved to optimality while a heuristic is employed for the distribution scheduling problem. Similarly, the coordinated problem is solved using a local improvement heuristic. The two approaches were applied to 132 distinct test cases with different values of the basic model parameters, such as the length of the planning horizon, the number of products and retail outlets, the cost of setups, the inventory holding costs, and vehicle travel costs. Results indicated that a 3–20% reduction in the total operating cost can be achieved by solving the coordinated production routing problem compared to sequentially solving the separate problems.

Later, Fumero and Vercellis (1999) proposed an integrated model for production and distribution planning, where both the integrated model as well as decoupled models are solved by similarly developed heuristic algorithms and compared. They generated 20 problem instances by randomly generating cost coefficients, over which they reported average savings for 18 problem sizes (varying by the number of customers, periods, and products) and three scenarios (varying by demand-to-production capacity ratio). The overall average saving was reported to be 10.2%.

Park (2005) solved both an integrated as well as a decoupled production and distribution planning problem heuristically. At first, he compared the heuristic with a mathematical model on small-sized problems. Then, the value of integration was evaluated through computational experiments on 21 test problems of different sizes (varying by the number of plants, retail outlets, products, and time periods), observing an average cost saving of 4.1% by integration. A sensitivity analysis on the problem input parameters was conducted and the results indicated that the value of integration was especially high in an environment of sufficiently large production capacity, high fixed cost per vehicle, small vehicle capacity, and high unit stockout cost. The observation regarding a high value of integration when the vehicle capacity is small seems contrary to the findings by Fumero and Vercellis (1999).

Boudia et al. (2006) developed a MA|PM heuristic as an approach to integrate the production and distribution decisions and compared its results with the H1 and the GRASP introduced in (Boudia et al., 2005a) and (Boudia et al., 2005b), respectively. They reported important savings regarding the two-phase classical approach H1: 13–18% for GRASP and 17–21% for MA|PM; however, they only provided 3 average results (savings) by each of the algorithms for three instances.

Then, an iterative approach to integrate the decisions was presented by Boudia et al. (2007a). It combines integer linear programming for the production plan and a tabu search for the distribution plan. First, the production plan is determined, and then the distribution is built considering the production plan as fixed. Afterwards, an improved production plan is determined while considering the distribution plan of the previous iteration. Then, a new distribution plan is computed given the new production plan. This iterative process continues until the two plans become stable. The authors reported cost savings on 48 numerical examples ranging from 3.5 to 27.7% compared to the two-phase classical (decoupled) method.

Marchetti et al. (2014) considered the optimization of enterprise-level production and distribution planning of industrial gas operations. The corresponding mathematical model was solved by the CPLEX solver (specifying an optimality tolerance) for two sequential approaches and one integrated approach. The paper provides results for both a single plant case and a multiple plant case, both solved with the two sequential and the integrated approach, and cost savings by integration are reported to be 4.1% for the single plant case and 9.9% for the multiple plants case. Both cost savings are calculated for a single real-world instance.

Du et al. (2019) solved the production routing problem to devise production and routing schedules that allow for flexible order composition and to ensure in-time delivery. An iterative sequential scheduling heuristic embedded with the local search was developed. Their numerical results show an average 11.6% reduction in the total cost compared to a scheduling method commonly used in practice.

### *3.3. Studies considering additional decisions*

A paper of Kuhn and Liske (2011) deals with a supply chain considering the supply of a production facility and production and distribution of an end item. This is known as the economic lot and supply scheduling problem, and the goal is to minimize the average overall cost per unit time. First, the authors developed a mathematical model for simultaneously solving the economic lot size problem and the vehicle routing problem, solved it with their $\varepsilon$-exact solution procedure, and reported advantages of the simultaneous planning compared with a sequential approach; however, they only provided graphical (not numerical) results, where the savings are seen to be in the range of 15–33%.

Hein and Almeder (2016) followed the work by Kuhn and Liske (2011) and faced an integrated planning approach that consists of the supply of raw material, production, and distribution planning. This contribution deviates from a standard production routing problem by considering the supply of raw materials. Based on 3888 test instances, the integrated approach was found to give better solutions than the sequential approach in about 72% of the instances. The authors applied a Wilcoxon signed-rank test to investigate significance of savings by integration. They concluded that the value of coordination grows as the problem size increases and, furthermore, if either of the three following costs rise: setup costs (i.e., reduction of setup operations), transportation costs, and holding costs. The effect of setup costs is most clear when holding costs are also high. On the other hand, coordination seems less beneficial if demand variation is high. Finally, as the study also compares the sequential and integrated approaches with a just-in-time (JIT) version, it is found that companies following the JIT principle may expect much higher gains from coordinated planning.

More recently, Darvish and Coelho (2018) dealt with a production-distribution system that focuses on location decisions in addition to the standard production, inventory, and distribution decisions. To solve the problem sequentially, they exploited several commonly used procedures based on separately solving each part of the problem, while the integrated problem is solved by both an exact branch-and-bound method and a matheuristic approach combining neighborhood search with exact methods. Two particular comparisons are provided: 1) the exact vs. the matheuristic algorithm for the integrated approach, where results are reported regarding the computational times and the relative performance of the algorithms, and 2) the sequential approach vs. the integrated approach, where the performance of the sequential approach is measured with respect to the upper bound of CPLEX. That is, the paper does not directly measure the savings of integrated planning.

### *3.4. Synthesis of findings*

To include a study in a meta-analysis on estimating the expected savings by integration, either of the following data must be available:

- Complete numerical results for individual instances on the savings by integration.
- Complete numerical results of both a sequential and an integrated approach for individual instances, so that the savings can be calculated for each instance.
- The average cost savings, the number of observations, and the standard deviation (std. dev.) of the savings.

Table 4 provides a summary of savings reported in the reviewed literature when comparing sequential and integrated approaches and the data instances used, respectively. It also provides notes regarding the availability of data for inclusion in the meta-analysis, including whether the data were available directly in the paper or provided by the authors upon request.

Chandra (1993) provided average savings over 33 groups of 25 random instances each, but no information on the standard deviations. I.e., in Table 4, we report 825 numerical observations (33 average savings values over 25 instances) and the average savings of 8.70% calculated as an average over the 33 reported average savings, but no information on the standard deviation, which is needed for further meta-analysis. Similarly, Fumero and Vercellis (1999) provided average savings for 54 groups of 20 random instances each. Boudia et al. (2006) reported three averages over 30 instances each, whereas Ruokokoski et al. (2010) presented a graph of results as well as a single average value. Kuhn and Liske (2011) included graphs with savings, but without any numerical data. Toptal et al. (2014) presented average savings for 75 groups of instances and Hein and Almeder (2016) for 272 groups. Darvish and Coelho (2018) provided no numerical results on savings and, finally, Absi et al. (2018) included 56 average savings calculated over four instances each, as well as one average saving over 96 instances.

**Table 4**
Assessment of inclusion of eligible papers based on data availability and data collection.

| Article | Data | Reported savings by integration | | | Integrated approach | Numerical results | |
|---|---|---|---|---|---|---|---|
| | Used instance | # num. observations | Average [%] | Std. dev. | | Incl. | Prov. |
| Chandra (1993) | Rand. gen. | 825 | 8.70 | – | Heur (iterative) | × | × |
| Chandra and Fisher (1994) | Rand. gen. | 132 | 9.12 | 3.60 | Heur (local improv) | ✓ | – |
| Fumero and Vercellis (1999) | Rand. gen. | 1080 | 10.19 | – | Heur (subgrad alg) | × | × |
| Park (2005) | Rand. gen. | 21 | 4.15 | 1.62 | Heur (based on (Chandra and Fisher, 1994)) | ✓ | – |
| Boudia et al. (2005a) | Rand. gen. | 90 | 11.71 | 3.73 | Coupled heur (H2) | × | ✓ |
| Boudia et al. (2005b) | By (Boudia et al., 2005a) | 90 | 15.93 | 3.29 | GRASP | × | ✓ |
| Boudia et al. (2006) | By (Boudia et al., 2005a) | 90 | 19,49 | – | MA\|PM | × | × |
| Boudia et al. (2007a) | Rand. gen. | 48 | 12.51 | 5.00 | Iterative (H2) | ✓ | – |
| Boudia et al. (2007b) | By (Boudia et al., 2005a) | 90 | 16.51 | 3.20 | RGRASP | ✓ | – |
| | Rand. gen. | 90 | 16.60 | 3.23 | GRASP + PR/S1 | ✓ | – |
| | Rand. gen. | 90 | 16.60 | 3.16 | GRASP + PR/S2 | ✓ | – |
| Boudia et al. (2008) | By (Boudia et al., 2005a) | 90 | 13.40 | 3.55 | H2/V2 | ✓ | – |
| Bard and Nananukul (2009b) | By (Boudia et al., 2005a) | 90 | 24.76 | 3.86 | Reactive tabu search | ✓ | – |
| Boudia and Prins (2009) | By (Boudia et al., 2005a) | 90 | 24.17 | 3.41 | MA\|PM | ✓ | – |
| Ruokokoski et al. (2010) | Rand. gen. | 1440 | 28.03 | – | Branch and cut | × | ✓ |
| Kuhn and Liske (2011) | Rand. gen. | – | – | – | Heuristic | × | × |
| Toptal et al. (2014) | Rand. gen. | 5960 | 10.12 | – | Tabu search | × | ✓ |
| Marchetti et al. (2014) | Real app. | 1 | 4.13 | 0 | CPLEX | ✓ | – |
| | Real app. | 1 | 9.92 | 0 | CPLEX | ✓ | – |
| Hein and Almeder (2016) | Rand. gen. | 3888 | 3.77 | | CPLEX | × | ✓ |
| Darvish and Coelho (2018) | Rand. gen. | 200 | – | – | Matheuristic | × | × |
| Absi et al. (2018) | By (Archetti et al., 2007, 2011) | 224 | 2.33 | – | Heur (iterative) | × | ✓ |
| Du et al. (2019) | Real app. | 11 | 11.56 | 5.79 | Heur | ✓ | – |
| Total papers/data files included for further statistical analysis | | | | | | 15/18 | |

*Note:* Rand.gen.-randomly generated; Num. res.- number of numerical results; Incl.-included: ✓ (included in the paper) or×(otherwise); Prov.-provided: ✓ (authors provided their data on our requested - in case they are not included) or×(otherwise).

## 4. Evaluation of research questions

The goal of meta-analysis is to merge results from several studies to obtain a more general and trustworthy result. In this analysis, a study is defined as results pertaining to a particular set of benchmark instances. Hence, one observation can be spread across several papers, presenting individual results for either integrated or sequential methods to solve particular instances. In one of the papers included, Hein and Almeder (2016) provided results for two different types of problems, which are here considered to represent two separate studies. Given that different types of instances are included in the analysis, with some variation in the definition of the exact problem solved, such as using different cost structures and constraints, the meta-analysis is based on a random-effects model (Turkeš et al., 2020, 2021).

### 4.1. Quantification of cost savings (RQ1)

The analysis is performed with the same statistical model as outlined by Turkeš et al. (2020). We define the effect size as being the percentage cost savings when solving an instance using an integrated method instead of using a sequential method. Considering a study $k$, we obtain information regarding the average effect size, $S_k$, the standard deviation of the effect size, $\sigma_k$, and the number of instances considered in the study, $N_k$. We then calculate the within-study variance $V_k = \sigma_k^2 / N_k$ as well as the between-study variance $T^2 = (Q - K + 1)/C$. Here, $Q$ is the sum of squares of the effect size estimates around their mean, weighted by $1/V_k$, $K$ is the number of studies included in the meta-analysis, and $C$ is a standardization factor (Turkeš et al., 2020). The weight of study $k$ is then $W_k = (V_k + T^2)^{-1}$, which is used to find the summary effect size $S$ by taking the sum of $W_k S_k$ divided by the total weights.

According to findings observed in the data collection phase, we merge results from papers (Bard and Nananukul, 2009b; Boudia et al., 2005a, 2005b, 2006, 2007b, 2008; Boudia and Prins, 2009) into a single study, given that all these papers are based on solving the same set of instances. Hence, to determine the value of integration for the problem studied, we select just the best available result for each instance.

Table 5 summarizes the results of the meta-analysis to quantify the potential cost savings by using an integrated method, with calculations adapted from the meta-analysis presented by Turkeš et al. (2021). The general conclusion on the expected cost savings provided by integration corresponds to 11.08%, with a 95% confidence interval [6.58%, 15.58%].

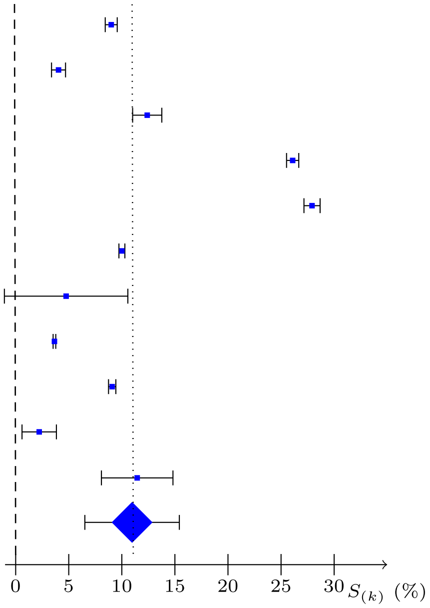
The forest plot in Table 5 also shows that most of the individual studies report a narrow confidence interval for the estimated effect size, corresponding to a low within-study variance, while the confidence intervals of different studies tend to not overlap, thus indicating a relatively high between-study variance. As the between-study variance is relatively high, the weights of each study become similar as the within-study variance plays a smaller role in the calculation of weights. The large between-study variance highlights the usefulness of applying a meta-analysis to estimate the potential cost savings from integration, as any individual study normally only represents the savings for one particular narrow setting, whereas the meta-analysis aims to estimate the expected savings across multiple possible scenarios where integration can be applied. In particular, six of eleven studies report average effect sizes that are not within the 95% confidence interval for the estimated expected effect size. This means that it is not reliable to use a single study as the basis for making statements regarding the expected savings of using integrated planning for production, inventory, and routing decisions.

### 4.2. General discussion on sensitivity analysis (RQ2)

When a large number of studies are aggregated in a meta-analysis, it may be possible to answer additional questions, such as the effect of particular characteristics of a study on the outcome. In this case, we

**Table 5**

Meta-analysis on savings by integration: $S_k$ - savings obtained from the data in study number $k$, $\sigma_k$ - standard deviation, $N_k$ - number of instances, $W_k$ - weight of the study.

| $k$ | Article | $S_k$ | $\sigma_k$ | $N_k$ | $W_k$ | Forest plot | 95% C.I. |
|---|---|---|---|---|---|---|---|
| 1 | Chandra and Fisher (1994) | 9.12 | 3.62 | 132 | 0.0176 |  | [8.50, 9.73] |
| 2 | Park (2005) | 4.15 | 1.66 | 21 | 0.0175 | | [3.44, 4.86] |
| 3 | Boudia et al. (2007a) | 12.51 | 5.05 | 48 | 0.0174 | | [11.08, 13.93] |
| 4 | (Boudia et al., 2005a, 2005b, 2007b, 2008; Boudia and Prins, 2009; Bard and Nananukul, 2009b) | 26.20 | 3.02 | 90 | 0.0176 | | [25.58, 26.83] |
| 5 | Ruokokoski et al. (2010) | 28.03 | 15.73 | 1440 | 0.0175 | | [27.22, 28.84] |
| 6 | Toptal et al. (2014) | 10.12 | 13.01 | 5960 | 0.0176 | | [9.79, 10.45] |
| 7 | Marchetti et al. (2014) | 3.97 | 4.23 | 2 | 0.0152 | | [ − 1.90, 9.83] |
| 8a | Hein and Almeder (2016) | 3.77 | 5.55 | 3888 | 0.0176 | | [3.59, 3.94] |
| 8b | Hein and Almeder (2016) | 9.20 | 8.85 | 1914 | 0.0176 | | [8.81, 9.60] |
| 9 | Absi et al. (2018) | 2.33 | 8.30 | 224 | 0.0175 | | [0.66, 4.00] |
| 10 | Du et al. (2019) | 11.56 | 5.79 | 11 | 0.0167 | | [8.14, 14.98] |
| | Weighted average | 11.08 | | | | | [6.58, 15.58] |

consider the number of available studies on the value of integration to be insufficient for a more refined meta-analysis. That is, stratifying the analysis based on some particular problem attribute leaves too few observations to generate a meaningful aggregation of results from existing studies. Instead, the second research question is evaluated by considering the relevant claims made in the individual studies.

As this analysis of individual parameters or ratios does not require access to detailed numerical results that can be aggregated over different studies, we can make use of qualitatively stated results from all the studies presented in Table 4, rather than the subset of studies included in the meta-analysis presented in Section 4.1. Table 6 summarizes the findings on the effect of particular attributes of the instances on the estimated value of integration.

**Degrees of freedom:** Altogether, several papers computationally show a general observation of benefits of integrating the production, inventory, and distribution decisions: the cost savings increase when the degrees of freedom in the system increases (numbers of products, customers, and time periods (Bard and Nananukul, 2009b; Boudia et al., 2007b; Boudia et al., 2008; Boudia and Prins, 2009; Chandra, 1993; Chandra and Fisher, 1994; Fumero and Vercellis, 1999; Hein and Almeder, 2016; Ruokokoski et al., 2010)).

**Cost parameters:** The cost savings are found to increase as the distribution costs increase (Chandra and Fisher, 1994; Hein and Almeder, 2016). Other observations do not seem to be consistent across all studies. For example, Chandra and Fisher (1994), Hein and Almeder (2016), Toptal et al. (2014), Ruokokoski et al. (2010)

**Table 6**

Parameters sensitivity reported in particular articles: Increasing of a specific parameter leads to increasing (↗) or decreasing (↘) of savings (value of integration) or has no influence at all (×).

| Article | Degrees of freedom | | | | Cost parameters | | | | Capacity parameters | | | Parameter ratios | | | | Others | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | $N^{Pr}$ | $N^{C}$ | $N^{T}$ | $N^{Pl}$ | $c^{D}$ | $c^{V}$ | $c^{H}$ | $c^{S}$ | $C^{V}$ | $C^{P}$ | $C^{IC}$ | $\frac{c^V}{c^D}$ | $\frac{c^D}{c^P}$ | $\frac{I^0}{I^L}$ | $\frac{c^{HI}}{c^{HE}}$ | $d^{S}$ | $o^{S}$ |
| Chandra (1993) | ↗ | ↗ | ↗ | | | | | | | | | | | | | | |
| Chandra and Fisher (1994) | ↗ | ↗ | ↗ | | ↗ | ↗ | ↘ | ↘ | ↗ | ↗ | | ↗ | | | | | |
| Fumero and Vercellis (1999) | ↗ | ↗ | ↗ | | | | | | ↗ | ↗ | | ↗ | ↗ | ↗ | | | |
| Park (2005) | | | | | | ↗ | ↗ | × | ↘ | ↗ | × | | | | | | |
| Boudia et al. (2005a, 2005b, 2006, 2007a) | | | | | | | | | | | | | | | | | |
| Boudia et al. (2007b, 2008) | | ↗ | | | | | | | | | | | | | | | |
| Boudia and Prins (2009) | | ↗ | | | | | | | | | | | | | | | |
| Bard and Nananukul (2009b) | | ↗ | | | | | | | | | | | | | | | |
| Ruokokoski et al. (2010) | ↗ | ↗ | ↗ | | | | ↘ | | ↗ | ↗ | | | | | | | |
| Kuhn and Liske (2011) | | | | | | | | ↘ | | | | | | | ↗ | ↗ | |
| Toptal et al. (2014) | | | | | | ↘ | ↘ | | | | | | | | | | ↗ |
| Marchetti et al. (2014) | | | | | | | | | | | | | | | | | |
| Hein and Almeder (2016) | ↗ | | ↗ | | ↗ | | ↘ | ↗ | | | | | | | | | |
| Darvish and Coelho (2018) | | | | | | | | | | | | | | | | | |
| Absi et al. (2018) | | | | | | | | | | | | | | | | | |
| Du et al. (2019) | | | | | | | | | | | | | | | | | |

*Note:* $N^{Pr}$ - number of products, $N^{C}$ - number of customers, $N^{T}$ - number of periods (length of planning horizon), $N^{Pl}$ - number of plants, $c^{D}$ - distribution cost, $c^{V}$ - (fixed) vehicle cost, $c^{H}$ - inventory holding cost, $c^{S}$ - setup cost, $C^{V}$ - vehicle capacity, $C^{P}$ - production capacity, $C^{IC}$ - capacity of inventory at customer location, $c^{P}$ - production cost, $I^{0}/I^{L}$ - ratio among central and local inventories, $c^{HI}/c^{HE}$ - ratio between holding cost of input material and holding cost of end item, $d^{S}$ - distance between suppliers, $o^{S}$ - order size.

observed that the cost savings decrease if the holding costs is higher, whereas Park (2005) found the opposite to be the case. Similarly, the cost savings have been found to increase as the vehicle costs increase by some studies (Chandra and Fisher, 1994; Park, 2005), but to move in the opposite direction in others (Toptal et al., 2014). Moreover, the effect of setup costs shown by Hein and Almeder (2016) are not in line with observations of Chandra and Fisher (1994), Kuhn and Liske (2011), Park (2005).

**Capacity parameters:** The cost savings increase when the available capacity at the plant increases (Chandra and Fisher, 1994; Fumero and Vercellis, 1999; Park, 2005; Ruokokoski et al., 2010). When the vehicle capacity increases, some studies suggest that the cost savings increase (Chandra and Fisher, 1994; Fumero and Vercellis, 1999; Ruokokoski et al., 2010), whereas one study suggests that the cost savings decrease (Park, 2005). Moreover, according to Park (2005), the capacity of inventories at customer locations has no influence to cost savings.

**Parameter ratios:** The benefits of integration have also been observed to grow with an increase in the ratio of fixed to variable transportation costs (Chandra and Fisher, 1994; Fumero and Vercellis, 1999), with the ratio between distribution and production costs (Fumero and Vercellis, 1999), with the ratio between central and local inventories (Fumero and Vercellis, 1999), and with the ratio between holding costs of input materials and holding costs of end items (Kuhn and Liske, 2011).

**Other parameters:** Finally, the savings by integration have been observed to increase as the distance between suppliers increase (Kuhn and Liske, 2011). Also, Toptal et al. (2014) found that savings increase when the order sizes increase.

Most of the findings for production-distribution problems seem to be valid for supply-production as well: Hein and Almeder (2016) showed that the value of coordination grows as supply-production problem size (number of input materials, end items, suppliers and the length of planning horizon) grows and capacity limits and holding cost decrease. The effect of setup costs are not as self-evident as argued by Kuhn and Liske (2011) but there is a visible tendency: savings decrease as setup costs decrease (Hein and Almeder, 2016).

Another point of view on the sensitivity analysis is to jointly compare tables 3–6. For example, it can be seen from Table 5 that results by some studies (Boudia et al., 2005a, 2005b, 2007b, 2008; Boudia and Prins, 2009; Bard and Nananukul, 2009b; Ruokokoski et al., 2010) are outliers with a higher than average effect, while other studies report a lower than average effect (Park, 2005; Hein and Almeder, 2016; Absi et al., 2018). However, by looking at the general description of the problem variants addressed, as outlined in Tables 3 and 4, there are no particular attributes of these studies that suggest an explanation for why their estimated value of integration differs from the estimated mean effect of integration.

However, to dive deeper into this matter we investigated each of the twenty papers mentioned in Table 4, identifying those studies where a detailed breakdown of the total costs was given for each data point. The goal of this was to seek a connection between the balance of cost components and the reported savings from integration, and we identified five individual studies where a breakdown of total costs into individual components was provided in some form.

Chandra (1993), whose results were reported without information about variance and was therefore not included in the meta-analysis, split costs into warehouse costs and distribution costs. The latter dominated, representing about 98.5% of the total costs. The reported savings of integration is 8.7%, which is within the confidence interval for overall savings obtained through the meta-analysis. Furthermore, since the savings were reported for classes of instances where the exact balance of cost varied, we could test whether the balance of costs influenced the savings of integration within this study. A linear regression model finds that within the narrow range of values investigated, the value of integration decreases by 1.1 percentage points when the relative warehouse costs increase by one percentage point, with a P-value of 0.054.

Chandra and Fisher (1994) also studies instances where distribution costs are dominating, being close to 99.5% of total costs. The savings of integration is 9.1%, which is also within the confidence interval of the meta-analysis. In the study of Park (2005), production costs are relatively high, representing about 64% of the total costs, while inventory costs are only 1–1.5% and distribution costs are around 32%. Given such a high emphasis on production costs, one could expect that the value of integration becomes relatively low, and this is in line with the reported savings of 4.2%, which is lower than the estimated expected savings from the meta-analysis.

Absi et al. (2018) has a case where production costs are even higher, constituting around 80% of the total costs, and with the remaining costs being split fairly equally among inventory and distribution costs. The reported savings of integration is a relatively low 2.3%. Running a linear regression on the individual results of Absi et al. (2018) allows us to analyze the effect of the relative costs in more detail. Within the study, we find that the relative ratio of inventory costs is statistically significant, and that the value of integration is reduced by 0.1 percentage points when increasing the relative inventory costs by one percentage point. Finally, in the study of Du et al. (2019), production costs make up around 33% and distribution costs 60% of total costs. The savings of integration is reported to be 11.6% in this case.

Summarizing the results from the five studies where total costs were explicitly broken down into different components, it seems that the value of integration may be lower when the relative cost of production is higher. While this is not sufficient to explain all the differences in reported savings among different studies, it does seem to explain, at least in part, why some studies describe average savings below the expected savings calculated from the meta-analysis.

Overall, however, the conclusion is that the current body of scientific literature does not contain sufficiently many studies that have focused on analyzing the effect of different problem characteristics on the value of solving an integrated problem. Table 6 suggests that certain attributes are relevant, but additional studies seem to be required to obtain better estimates of how much these attributes can affect the expected cost savings from applying an integrated method.

## 5. Conclusions

This paper quantifies the potential savings by integrated planning compared to sequential planning when jointly considering production, inventory, and routing decisions. A systematic review and a meta-analysis serve as suitable mechanisms to quantify the results on cost savings and to deduce for which problems and parameters setting it is more relevant and beneficial to solve the problem with an integrated approach.

The main finding is that the expected cost reduction from using integrated planning is estimated to 11.1%. This is found by aggregating results from 11 different studies, spanning 15 different articles. However, the individual studies report a wide variety of average savings, ranging from 2.33% to 28.03%, meaning that there is still some uncertainty surrounding the expected cost reduction, and a 95% confidence interval for the expected savings is found as [6.58%, 15.58%]. A meta-analysis may become biased. One source of bias is that some studies may have been performed but not published. For example, if a study finds that the integrated method does not provide significantly lowered costs compared to a sequential method, the authors may choose not to publish the comparison at all, leading to a publication bias.

The twenty papers included in the systematic review are analyzed to find which attributes of the problem instances influences the value of integration. For example, the value of integration seems to be higher when there are more products, more customers, or a longer planning horizon. It also increases when distribution costs or fixed vehicle costs are higher, while it decreases when inventory holding costs are higher. The production capacity also influences the potential for savings with integration, with a higher production capacity leading to a higher potential for cost savings.

In this work, a comprehensive statistical analysis of the influence of each attribute was not attempted, as this would require using more detailed data from each study. Thus, as data availability prohibited a purely quantitative analysis of these studies, these results can be considered as preliminary indications, and further research is needed to better understand the effect of different problem attributes on the expected value of integration. Nevertheless, by examining in detail the breakdown of costs into individual components, as permitted from the data of five individual studies, we found indications that the value of integration is partly governed by the relative contribution of production costs: when production costs are relatively high the use of a sequential approach can be justified.

The realization that an integrated approach has an expected cost saving of 11.1% is clearly useful for guiding future research on production and inventory routing problems. The research literature is already filled with contributions that address integrated planning problems, without comparing to sequential planning. When solving integrated problems, the expected cost saving instates a bound on the acceptable optimality gap for the methods applied: unless the gap is lower than 11.1%, a sequential approach may provide competitive results at a much lower computational effort.

Out of the 20 papers included in the systematic review, only two solved problem instances based on real-world data, whereas the other 18 relied on randomly generated instances. This is clearly a limitation of the systematic review and the meta-analysis performed, and it should be strongly encouraged to perform additional studies using real data, to increase our confidence with respect to the estimated expected cost savings. If further studies are completed in the future, the meta-analysis performed can be updated to reflect an increased body of knowledge. Since this systematic review was unable to convincingly conclude regarding which circumstances lead to a higher or lower value of integration, there is clearly still ample room for additional studies that can help us to further understand and measure the potential benefits of solving an integrated problem.

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