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Published in the Proceedings of the 13<sup>th</sup> International Conference on Modern Information Technology in the Innovation Processes of Industrial Enterprises MITIP2011, Trondheim, Norway, June 22–24 2011, pp. 20–29.

Bib<sub>T</sub>E<sub>X</sub> entry:

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@inproceedings{Kemeny_et_al_2011
  author    = {{Zs.} Kem\'{e}ny and E. Ilie-zudor and J. F\'{u}löp
              and A. Ek\'{a}rt and C.D. Buckingham and P.G.Welch},
  title     = {Multiple-participant hub-and-spoke logistics networks:
              Challenges, solutions and limits},
  booktitle = {Proc. of the 13th Int. Conf. on Modern Information
              Technology in the Innovation Processes of Industrial
              Enterprises MITIP 2011},
  address   = {Trondheim, Norway},
  pages     = {20--29},
  year      = {2011}
}
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## MULTIPLE-PARTICIPANT HUB-AND-SPOKE LOGISTICS NETWORKS: CHALLENGES, SOLUTIONS AND LIMITS

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### Abstract:

*Hub-and-spoke logistics networks can bridge the gap between potentially conflicting requirements of low shipping costs, fast delivery and small consignment sizes. However, the composition of hub-and-spoke networks does present new problems to be handled. Being a work-in-progress contribution, the paper presents the ADVANCE FP7 EU project and its focal areas related to hub-and-spoke logistics networks: exploiting information implicitly present in the network for an improved utilization of resources, mainly on an operational level.*

### Keywords:

*hub-and-spoke networks, networked enterprises, global optimization, prediction*

### INTRODUCTION

Experience of the past decades has suggested that the majority of freight transport underlies recognizable relations between the size (type) of freight and commonly required modes (mostly timing) of delivery. Often, the size-dependent classification of *parcel/express delivery* of small goods, *less-than-truckload delivery* of boxed or palletized goods, and *full truckload delivery* in dedicated vehicles is cited (Wieberneit, 2008). The handling of small shipment units is economically only feasible if some kind of *bundling* is performed, i. e., several smaller shipment units are transported together in the same process. While the introduction of intermediate *cross-docking* stations makes it possible to serve several sources and destinations by re-assembling the bundled contents as required for the routing of the individual shipment units, adding further stages to the shipping process is certain to increase the overall delivery time. Fast and affordable shipping of small freight units thus seems to impose conflicting requirements.

Nevertheless, the market niche characterized by the above criteria does represent a growing demand, and the past decades have shown that it is possible to answer them in an economically feasible way. A tried-and-proven solution to the above problem is the operation of a core network of fast sorting facilities that can perform cross-docking operations in keeping with time limit guarantees, extended by a periphery of local pick-up and delivery services. This arrangement is commonly referred to as a *hub-and-spoke* network (Zäpfel and Wasner, 2002), the core facilities being the *hubs*, and local operations being performed by *spokes*. In some cases, the nature of operations is strongly reflected in the organizational structure as well: a major player operates the hubs, while spoke-related services are contracted out to smaller partners who can better adapt to varying local conditions and may react faster to changes due to their compact size and lean decision structures (Zäpfel and Wasner, 2002).

Nevertheless, drawbacks inherent to organizational heterogeneity do surface, and may impose limits on overall performance and efficiency of the network. The EU FP7 project ADVANCE aims to find remedies to selected problems of such logistics networks, focusing on the potential of information transparency, as well as modeling, optimization and prediction techniques not yet commonly used in this field. The recent beginning of the three-year project (October 2010) has not yet provided findings that would go beyond a work-in-progress report—therefore, this paper is only meant to provide an insight into initial findings and planned work. The next section presents the problem domain in more detail with respect to terminology, typical processes and targeted problems. Hereafter, the goals of the ADVANCE project are outlined, presenting focal areas of planned improvement, along with the selected means of eliciting these advances.

## HUB-AND-SPOKE NETWORKS AND RELATED PROBLEMS

### Fundamental processes

A *hub-and-spoke* logistics network consists of *hubs* performing transshipment operations (i. e., reassembling and redirecting compound shipments of smaller consignment units), and *spokes* or depots linking end customers with the hubs. Typically, shipping processes in a hub-and-spoke network follow this sequence (Zäpfel and Wasner, 2002), also summarized by Figure 1:

- *Stage 1*—Depots pick up shipments at their customers. This is usually carried out in the form of *pickup tours*, serving several customers within the same round-trip. While the number and routing of pick-up tours is left to the depot (and may be subject to operational decisions as well as route optimization), by the end of this stage, all shipments of a given time period must be present at the depot where they are readied for transport to the hub.
- *Stage 2*—This stage is, in fact, a complex procedure containing the following sub-stages:
  - Haulage from the depots of origin to the hub;
  - Rearrangement (cross-docking, transshipment) of goods from several depots to assemble new shipments that contain items with the same depot of destination;
  - Haulage from the hub to the depots of destination.

Note that usually, the same vehicles perform both depot→hub and hub→depot haulage in subsequent steps. This implies that a balance of inbound and outbound traffic is needed to minimize deadheading traffic. Delivery time constraints, however, impose limits on simple load balancing by withholding a certain number of consignments. Also, imbalance of longer duration or bursts of critical volume are certain to surpass the dimensions where temporary withholding would be a feasible option.

Another operational issue resulting from this arrangement is the need for sufficient haulage capacity to perform this stage: a sufficient number of vehicles must be present at the hub by a certain time limit to carry out the hub→depot step. If needed, additional vehicles must be called in (typically from the destination depot) to handle the volume scheduled for the given period.

- *Stage 3*—Once the shipped goods are at the disposal of the destination depot, delivery to the destinations is performed. Again, it may be left to the given depot how this is carried out—a delivery tour may also be combined with a pickup tour to improve vehicle utilization or reduce time lags.

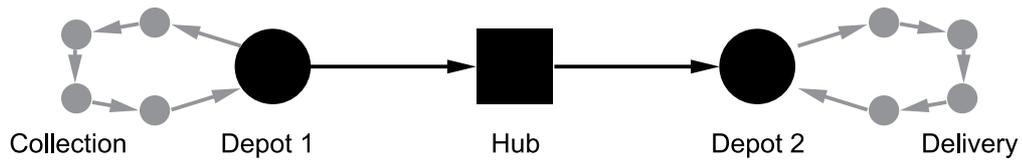


Figure 1: Typical stages of shipping in a hub-and-spoke network: collection by Depot 1, shipping from Depot 1 to the Hub, cross-docking of shipments at the Hub, shipping from the Hub to Depot 2, and delivery to destinations in the delivery area of Depot 2.

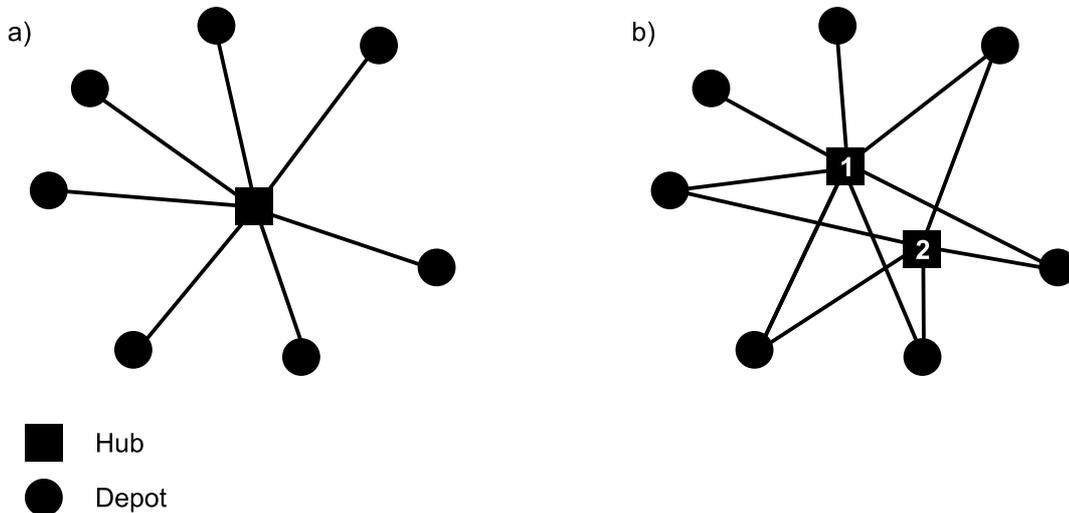


Figure 2: Single allocation (left) and multiple allocation (right) of depots to hubs in a hub-and-spoke network.

### Classification and special cases

Hub-and-spoke networks can be classified by their topology, i. e., the arrangement and number of hubs and spokes, as well as their connectivity. In a “pure” hub-and-spoke case, the sending and receiving depots may be assigned to a single hub (referred to as the *single allocation* case), or they may serve several depots (*multiple allocation*, see also Figure 2). Note that the multiple allocation case does not require *per se* that each of the depots be connected to each hub—where full multiple allocation is not the case, dispatching decisions must be met in accordance with the partial connectivity, and allocation must be, naturally, known prior to these decisions (de Camargo et al., 2008, 2009). Nevertheless, connectivity patterns should preferably remain unchanged for a longer period of time.

In practice, the restrictions of pure hub-and-spoke type are often relaxed by the introduction of additional connections (Lin et al., 2003; Liu et al., 2003; Lumsden et al., 1999; Wasner and Zäpfel, 2004; Zäpfel and Wasner, 2002), see also Figure 3. *Hub-to-hub trunking* may occur if the size or topology of the network makes this a sensible choice (e. g., in the case of intercontinental transport where a segment of overseas transportation is inserted, and at least one hub is maintained on each continent concerned). Also, dispatching errors or mitigation of bottle-necks may require occasional hub-to-hub haulage in networks of the multiple allocation type. Nevertheless, it should be kept in mind that hub-to-hub trunking introduces one more leg in the path of individual shipments and thus extends total delivery time—therefore, it is generally avoided in cases where time limits are tight.

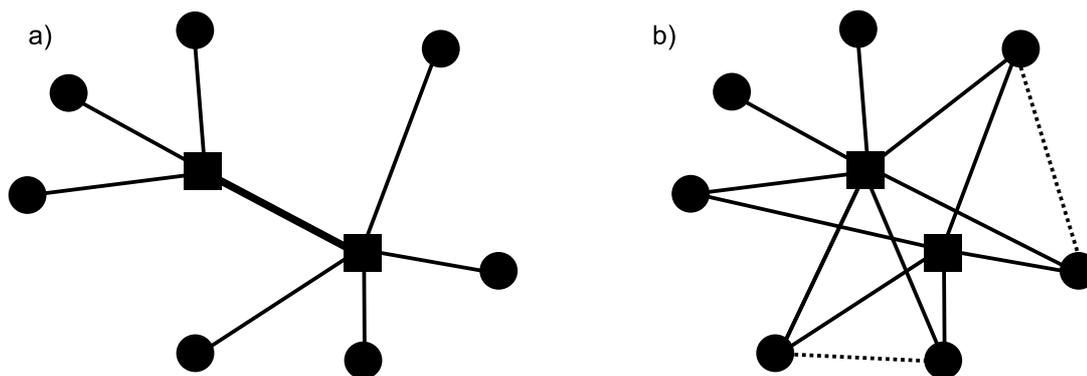


Figure 3: Extensions to a pure hub-and-spoke layout: hub-to-hub trunking (left; marked with a thick line), and direct depot-to-depot connections (right, dotted lines).

Another possible addition to strictly hub-and-spoke operation is direct depot-to-depot traffic (see also Figure 3)—again, characteristics of network topology may make this reasonable, especially if consignment volumes of the given depot-to-depot connection are large enough for economic vehicle utilization. If depots operate as subcontractors of an enterprise running the hubs, direct depot-to-depot traffic may not even be perceived by the hub.

While the extension of pure hub-and-spoke networks may appear a subtle addition, it usually exerts a strong influence on the underlying mathematical models of network dynamics, similarly to the effect of purely quantitative aspects (capacity limits, etc.). This can be traced back to a variety of reasons. At this point, it may be enough to consider that compliance with certain network performance constraints can be reached in totally different ways if additional connections relax the strict hub-and-spoke nature. In some aforementioned cases, critical events were mitigated by temporarily lifting pure hub-and-spoke restrictions—holding on to these could potentially require much larger network capacities to handle the same problems.

### Decision levels

Setting up and operating a hub-and-spoke network requires numerous decisions—it is widely accepted to classify them by the following two levels:

- *Strategic decisions* are dealing with the layout, long-term properties and dimensions of the network. Typical subjects are:
  - Number, location, capacity of hubs, depots and vehicles;
  - Assignment of units (primarily depots) to locations to be served;
  - Layout of transportation routes;
  - Settling on business models and rules of operation.
- *Operational decisions* are taken to meet the demands of daily operation, typically:
  - Allocation of storage and transportation resources to handle current demands (as we will see, this is especially important and time-critical for hubs calling in the depots' vehicles to cover outbound traffic);
  - Vehicle routing, e. g., planning (and combination if needed) of pickup and delivery tours by depots (Bastian and Rinnooy Kan, 1992; Bertsimas, 1992);
  - Instant response to exceptional or critical cases (e. g., recognized errors, failures or capacity shortages).

## Problems prevailing in sub-contracted cases

Especially if hub-and-spoke networks are operated with sub-contracted depots having their own business interests and demands for privacy, network coordination and resulting efficiency may experience limits that could, in many cases, be lifted by improved application of today's resources:

- The organizational heterogeneity of the depots (different policies, unique identifier formats, handling and modeling of shipment information, etc.) impairs interoperability. Aside from data models, this also covers reliability, the timing of sharing information, etc. It is enough to think of different possibilities of communicating expected inbound traffic: some depots may carry this out as shipments are ordered, while others may wait until actual pickup, or completion of the pickup tour (e.g., no communications connection while vehicle is on its way). Most aspects of interoperability cannot simply be improved by contract (e.g., requiring updates at well-defined intervals), as a major part of uniformization depends on successful adoption of the required interfaces and policies in individual cases with varying IT legacy.
- Multiple-participant networks can suffer from information not being present in a given place at the right time (in other words, the data flow may lag behind the material flow), causing inefficient or unbalanced use of transportation assets due to sub-optimal decisions. This is especially critical if—as usual—the same vehicles perform both depot→hub and hub→depot traffic and leave/arrive by the same schedule. Here, it may pay off to provide information (even if only partial or preliminary) as soon as possible to allow timely response to sudden out-of-balance situations (see also Figure 4). Nevertheless, establishing such a degree of information transparency can be demanding, especially for the hubs, as—potentially large—data sets need to be sorted, rearranged and forwarded in due time to facilitate adequate allocation of physical resources (i.e., transportation assets). In current practice, even plain information flow is not self-evident across company borders and is often lagging too much behind the dispatching of shipments.
- A large network suggests that the amount of data will present challenges as well, in addition to the need for surveying longer time ranges (e.g., to detect trends or patterns). Massive but low-level information must be filtered or pre-processed to make it suitable for decisions, forecasts, etc. In today's practice of hub-and-spoke networks, this is hardly done and the potential of implicit knowledge of demand dynamics and dependencies remains largely unexploited.
- Confidentiality issues may also surface in a network, the more so as some members collaborating within the network may be each other's competitors on other services. Inference attack has also been identified as a potential threat of such cases (Vora, 2007), and often, no clear border can be drawn between fair use of partners' information to improve network operation and data mining delivering details the partners originally intended to withhold for their own competitive survival. While participants, therefore, strive to disclose a safe minimum of information (often on a need-to-know basis), it may be possible to find agreeable alternatives e.g., by anonymization or privacy-preserving techniques as separating shipment volumes from particular destinations
- Making participation attractive for local partners may conflict with overall network efficiency, possibly ruling out some methods of reaching global optimum. This hindrance is well-known in other related domains, such as supply chain management, and has been addressed by various contracting policies that guarantee the fair sharing of risks and profits within agreeable tolerances (Krajewska and Kopfer, 2006).

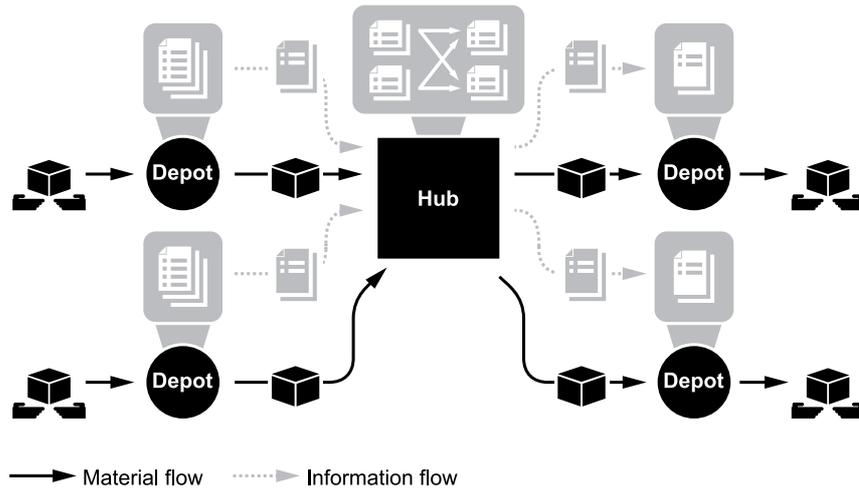


Figure 4: Information transparency in hub-and-spoke networks requires data streams comparable to material movement

## GOALS OF THE “ADVANCE” PROJECT

The *ADVANCE* project, financed within the EU 7th Framework Programme, addresses several of the aforementioned shortcomings by developing an open-source solution framework that supports networked enterprises mainly on the operational level. Working closely with the UK-based logistics company *Palletways* gives researchers within the project consortium an excellent background for in-depth field studies of requirements and limitations in today’s logistics networks, and allows objective testing of pilot applications. Here, we list the main contributions that are expected to be delivered during the project.

### Implementation fundamentals: runtime environment and flow editor

The envisaged “framework” character of the solution package developed in *ADVANCE*, as well as the targeted area of use being networks of collaborating enterprises, imply that prospective users have to be provided with versatile tools adapting to the data models employed in the given application. To this end, a modular concept is being pursued that facilitates the re-use of pre-defined data models and the easy creation of new ones fitting the needs of the given application, and support for assembling a complex solution from generic building blocks and case-specific algorithms in connectible envelopes.

*ADVANCE* pursues the use of a network-specific data model that is versatile enough to allow all locally used models to be mapped onto it—in fact, images of local data models are derived from a generic network-wide model by specialization (i. e., restrictions placed on certain elements of the generic model). This makes it possible to handle data model variations by standard procedures which building blocks can be prepared for, even prior to assembly of larger processing structures. Within the *ADVANCE* project, one example of a network-wide generic data model will be developed that suits the requirements of pilot implementations, and experience gained in the process will be available to serve as a guideline for other communities developing their own model, or modifying the project-specific example to fit their own needs.

In parallel with ongoing efforts of setting up a generic data model, a *flow editor* is being developed, providing an environment with an intuitive graphical interface for the assembly of more complex structures from individual building blocks, the “flows” being the connections established between these elements. Here, two groups of blocks will be provided:

- *Domain-independent, generic blocks* with basic functionalities as switching, buffering, aggregation of data flows, or fundamental operations on flows/data sets that appear in most, if not all, specific applications. Also, some of the compound blocks with more sophisticated functionalities will be well-suited for reuse: since machine learning and data mining techniques are, by nature, less domain-dependent, examples elaborated for specific needs in ADVANCE will suit a wider spectrum of other applications without too much additional fine-tuning.
- *Specific blocks* tailored to the given domain of application. A preliminary survey and past experience in mathematical problems related to the focal domain of hub-and-spoke networks have shed light on the fact that prevailing practice in certain fields (most importantly, *optimization*) still relies on highly specialized solution algorithms that can be far less portable than other functionalities of comparable complexity within the framework. While ADVANCE cannot realistically aim for a major breakthrough in this regard, proper documentation will be provided to guide the users through these highly specific in-house implementation cases once they are deemed necessary in the given application.

Once the blocks are in place and connections have been defined, an underlying runtime environment will put the building blocks to work. The runtime environment is planned to be as generic as possible, making provisions for the entire spectrum of functionalities that may surface during the project, or at subsequent elaboration of solutions in related application fields.

### Exploiting low-level information

A well-recognized characteristic of logistics networks, especially of the multiple-participant kind in the focus of ADVANCE, is that the large amounts of—possibly heterogeneous—low-level operational information distributed all over the network is sparsely exploited for the global benefit of the network or the partners concerned. Several properties can be identified as potential obstacles to the aforementioned utilization:

- Data to be exploited are low-level and present in large amounts, while the measures of improvement they could contribute to require a high degree of organization/structuring, high content of relevant information (and, usually, smaller total data volumes due to their higher “density”). It is enough to think of disjoint reports of discrete shipping events vs. aggregated and structured turnover data—the discrepancy between these can be clearly recognized.
- Data contributing to one and the same piece of structured information can be distributed over several locations (e. g., event logs concerning a day’s depot→hub shipments with the same destination depot), and it may not even be known at a central processing point which peripheral locations relevant data would have to be elicited from (i. e., either “push” or “pull” mechanisms of an information flow are hampered already by the distributed nature of raw data alone).
- Data may contain relevant information in an *implicit* way, e. g., gaining insight may require one to examine *relations* between raw pieces of data and only then make the findings (e. g., recognized timing or event dependencies) explicit.
- Data, especially low-level operational information, may remain where it is created and directly used in its original form, even if it could have contributed to improved decisions at higher levels of the network. While a partner’s fear of disclosure is more difficult to cope with, sometimes, data are not being forwarded merely due to expected difficulties of processing it in its original form—in the end, information that is, after all, present in the network does not appear at the proper time and place for correct high-level action.

In the ADVANCE project, a set of several techniques is planned to handle such situations:

- *Data mining techniques* will be employed to survey local, low-level information and extract what needs to be forwarded. However, data mining can, in some cases, border on obtaining confidential information by inference (Vora, 2007)—in this regard, guarantees have to be given to future users, and existing agreements or regulations must be observed.
- *Preserving privacy* can be made a part of the methods employed. In order to grant such privacy-preserving properties, exact examinations have to be carried out with respect to trimming down the information necessarily required for the given case, and stripping it of any other data that could potentially violate the desired level of privacy (e.g., preliminary destination information could be narrowed down to specifying the destination depot only, not disclosing the exact identity of receiving customers).
- *Machine learning techniques* often go hand-in-hand with data mining, especially if implicit information is made explicit by setting up a model of a (sub)system's behavior and comparing estimations with phenomena actually occurring. While such models can also be employed for on-demand forecasts of process characteristics (Carbonneau et al., 2008), they can also be relied on when relevant information (i.e., deviations from the "ordinary" case expected) has to be detected and extracted, typically from a data flow of larger throughput.

### **Decision support on the operational level**

The lack of up-to-date and correct information can lead to wrong operational decisions, such as unsuitable preparation for upcoming loads by improper (pre)allocation of resources. One of the main contributions of the ADVANCE framework will be that it would be able to obtain such crucial information (also in ways not being feasible before), and present it to operators and decision makers in a usable form. This is, in general, referred to as *decision support*.

ADVANCE envisages to realize decision support functionalities in various forms, whatever is adequate for the given situation: where needed, (model-based) prediction produces forecasts that can be reviewed in detail by personnel in charge, in other cases, warnings are issued to call the operator's attention to the coming need for intervention, etc.

Nevertheless, it is recognized that the usability and evolvability of decision support depends much on the ways the artificially produced results fit into the operator's own mental context (i.e., a practical "picture of the world" with characteristic expectations, occasional simplifications or biases). The failure of some decision support systems did, in fact, arise from the fact that users were not able to assess the validity of the machine-produced responses in their routine context, in other words, the reply "did not make sense", even though it might have been technically correct. Not only does this keep the user from effectively overriding the support system's errors, it also hampers the evaluation of the system's quality of support, not enabling the system to *learn* from human assessment and *evolve* (Mohammed et al., 2007).

In the ADVANCE project, *cognitive models* of human reactions are employed to bridge gaps in human interpretability and feedback to the decision support system, laying out the formulation of machine output while keeping characteristics of human comprehension, attention or misconceptions in mind.

### **Outlook towards strategic improvement**

The organizational heterogeneity of logistics networks (more specifically, members preferring some of their own goals or limits over global network performance) is known to keep some characteristics or working processes of the entire network from being optimal. This phenomenon (also well-researched e.g., in game theory) is widely known, even far beyond the domain of logistics—it may be enough to mention difficulties of multiple-player coordination or prevention of the *bullwhip effect* in supply chains, which can all be traced back to the aforementioned

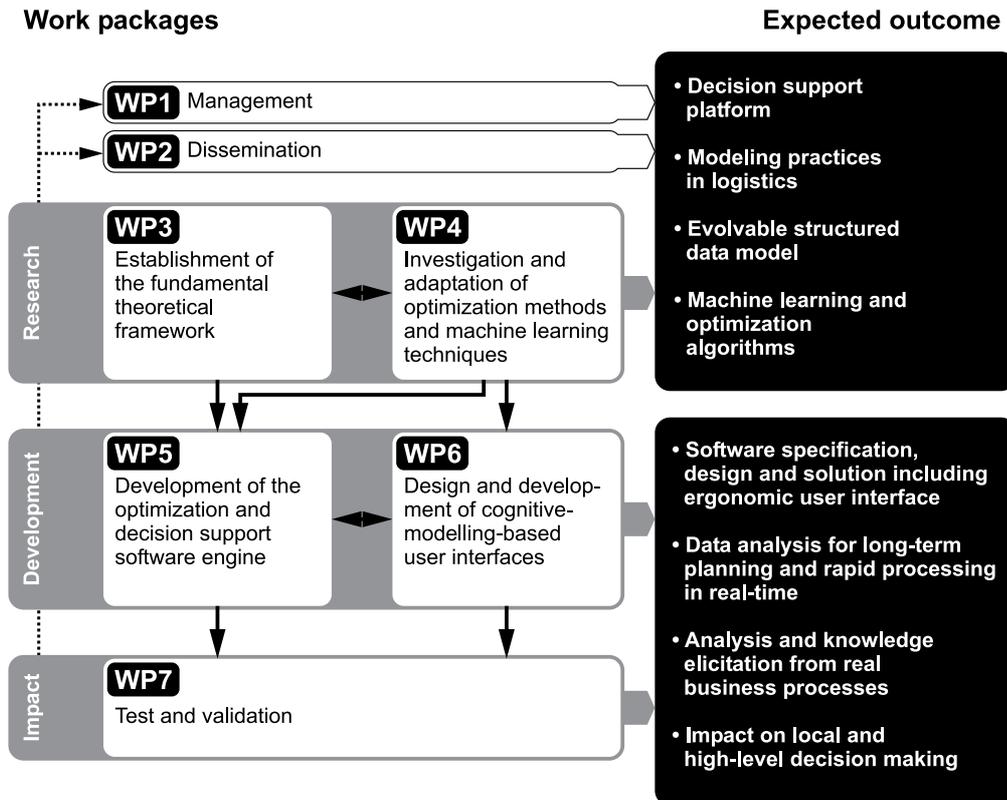


Figure 5: The ADVANCE project at a glance—summary of work packages (left) and expected results (right).

behavioral limitations. Remedies to such shortcomings belong to the layer of *strategic decisions*, as these effect lasting structural and procedural changes beyond everyday operation (Crujssen and Salomon, 2004; Krajewska et al., 2008).

An exhaustive examination of these strategic issues lies outside the scope of ADVANCE, nevertheless, it can already be foreseen that some additional insight into strategic matters will result as a by-product of advances of the operational level. Wherever possible and reasonable, ADVANCE will call attention to the perceived problems, and may propose possible actions to be taken (e. g., revised participation contracts, guiding to desired behavior by additional benefits, suggested sharing of profits and risks), along with an estimation of their impact.

## CONCLUSION

Hub-and-spoke logistics networks allow companies to fill niches in the logistics industry with requirements perceived as conflicting by many large-scale forwarders. However, this is achieved at the cost of new challenges surfacing due to the composition of hub-and-spoke networks. Aside from a survey on typical problems, the work-in-progress paper presented the ADVANCE project and its focus on selected problems related to application domain and the main scenarios in the focus of ADVANCE. The primary topic of the project is the improved utilization of network resources in given hub-and-spoke scenarios. To this end, low-level information implicitly present in the network will be exploited by selected modelling and prediction techniques that facilitate operational decisions. Preliminary studies revealed a strong dependence of adequate methods on characteristics of the specific business cases, therefore, the project will deliver its pilot solutions within a framework that will allow prospective users to depart from the base functionalities employ solutions specific to their own needs.

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