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Toward smart manufacturing scheduling from an ontological approach of job-shop uncertainty sources

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Abstract: An integral application of the enabling technologies of Industry 4.0 in the job-shop scheduling problem (JSSP) must contemplate the automation and autonomy of the involved decision-making processes as a goal, which is the main purpose of the smart manufacturing scheduling (SMS) paradigm. In a real production context, uncertainty acts as a barrier that hinders this goal being met and, therefore, any SMS model should integrate uncertainty generators in one way or another. This paper proposes an ontological framework that identifies and structures the entities shaping the joint domain formed by the job-shop scheduling process in its itinerary toward the SMS paradigm, the sources of uncertainty that it faces, and the interrelationship type that link these entities. This ontological framework will serve in future research as a conceptual basis to design new quantitative models that, from a holistic perspective, will address the stochasticity of manufacturing environments and incorporate the management of disturbances into the real-time resolution of automatic and autonomous job-shop scheduling.

Keywords: Industry 4.0, smart manufacturing scheduling, job-shop, scheduling, stochastic, disturbance, disruption, zero-defect manufacturing, digital twin, ontological framework.

1. INTRODUCTION

Job scheduling is a decision-making process that plays an important role in production, and always involves a set of tasks to be performed, as well as a set of available resources to perform these tasks. In the specific manufacturing context in which job scheduling develops, there are many identifiable sources of uncertainty that impact production processes and, therefore, scheduling processes themselves. Nevertheless, stochastic scheduling models are often ignored in practice.

Indeed, most scheduling support systems, such as those implemented into main enterprise resource planning (ERP) systems, adopt a deterministic and, to a greater or lesser extent, a simplifying approach which, together with other factors, allows a gap to open between the stochastic problem and the deterministic solution (Baker and Trietsch, 2007). Without sufficiently detailed and precise knowledge of the stochastic problem, it is not feasible to know the magnitude and characteristics of the existing gap for the deterministic solution. This indeterminacy plays a key role in the scheduling function. Ignorance of the shop floor environment's stochasticity is at the root of some problems that planners encounter while going about their mission when the schedule becomes unfeasible due to unexpected events (Usuga Cadavid et al., 2020). Thus, in today's industrial scenarios influenced by the Industry 4.0 paradigm, it follows that the modeling of automatic and autonomous scheduling systems has to be sensitive to the stochastic characteristics of the shop floor environment, which can be approached from several perspectives; *e.g.* the classic and frequent extension of deterministic models based on the individual addition of stochastic terms to the job scheduling problem, such as rush orders or machine breakdowns; or other different approaches in which an eminently stochastic view of the shop floor predominates, such as the safe scheduling of Baker and Trietsch (2007), which suggests taking into account safety times in scheduling policies as a strategy to better practically represent the stochastic reality. Both perspectives, and despite the disparity of their approaches, coincide in one aspect: although both are approaches that study this stochastic reality to understand and model it, they do so without addressing the possibility of mitigating it, or how to go about doing so.

Conversely, other perspectives present in the literature suggest the possibility of acting first on the shop floor stochastic circumstance to mitigate its effects before modeling the scheduling system. This is the case of SMS (Serrano-Ruiz et al., 2021b), which promotes the ZDM model to guide shop floor management toward zero disturbances and zero interruptions to first optimize production processes by mitigating their stochastic reality and to, thus, facilitate the subsequent modeling, implementation, and operation of automatic and autonomous scheduling systems. In the SMS context, different approaches exist with the potential to move toward a zero-disturbance and zero-disruption production scenario. In them, however, knowledge sharing and reuse would be useful for starting with the definition of the common vocabulary in which shared knowledge will be represented. The specification of a representation vocabulary for a shared domain of discourse, i.e., definitions of classes, relations, functions, and other objects, is called an ontology (Gruber, 1993). One of the main purposes of ontology development is to construct new knowledge-based systems instead of constructing new knowledge bases from scratch, which can be done by assembling reusable components, in this case, pre-

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existing knowledge bases (Neches et al., 1991). Yet employing ontological frames to share a certain domain also enables interoperability between systems by allowing declarative knowledge, problem-solving techniques and reasoning services to be shared (Neches et al., 1991) and by, thus, mitigating the generation of failures caused by a deficient interrelation of systems from resorting to different vocabularies, entity classifications, relationship definitions or functions. In line with this, the present paper presents and describes an initial ontological framework that identifies and structures entities by constituting the joint conceptual space shaped by the job-shop scheduling process in its itinerary toward the SMS paradigm, the sources of uncertainty that it faces, and the type of interrelationships that link these entities.

The rest of the article is structured as follows. Section 2 introduces an overview of the related literature. Section 3 proposes the SMS setup with an ontological approach and presents the vocabulary, classes, attributes, and relationships that shape the ontological framework. Section 4 discusses the main findings and implications. Section 5 concludes and identifies future research lines.

2. LITERATURE REVIEW

The literature on scheduling in production environments subject to stochasticity, uncertainty, randomness, disturbances or disruptions abounds. However, publications on that domain that present ontological content are scarce. Specifically, the search for journal articles and conference papers in English present in the Scopus and Web of Science databases involving the concepts "manufacturing", "schedul*", "sequenc*", "uncertain*", "random*", "disturb*", "disrupt*", and "ontolog*", provided 12 results, dating from 2008 to 2021. All of them are listed in **Table 1**.

Table 1. Literature related to scheduling ontologies in productions environments subject to stochasticity

	Author	Title
1	Wang et al., 2008	A PSL ontology-based shop floor dynamical scheduler design
2	Jana et al., 2013	Dynamic schedule execution in an agent based holonic manufacturing system
3	Zhu and Roy, 2015	Ontology-based disassembly information system for enhancing disassembly planning and design
4	Qu et al., 2016	Learning adaptive dispatching rules for a manufacturing process system by using reinforcement learning approach
5	Xue et al., 2017	Event-driven dynamic job shop scheduling execution based on improved genetic algorithm and ontology
6	Barenji and Li, 2019	An agent-based approach to dynamic scheduling and control for a flexible system
7	Saeidlou et al., 2019	Knowledge and agent-based system for decentralised scheduling in manufacturing
8	Peng et al., 2020	The research of flexible scheduling of workshop based on artificial fish swarm algorithm and knowledge mining
9	Mabkhot et al., 2020	An ontology-based multi-criteria decision support system to reconfigure manufacturing systems
10	Chen et al., 2021	A hyper-heuristic algorithm based genetic programming for steel production scheduling of CPS-oriented
11	Li and Tang, 2021	A semantic-level component-based scheduling method for customized manufacturing
12	Saeidlou et al., 2021	Towards decentralised job shop scheduling as a web service

The research of Wang et al. (2008) starts with an uncertain dynamic manufacturing environment to present a design framework of a shop floor dynamical scheduler. It works according to a multistep adaptive scheduling strategy and a process specification language, which is an ontology-based representation of the process plan. The dynamic job allocation strategy of Jana et al. (2013) for machine scheduling in a multi-community and multi-objective job-shop environment follows an agent-based holonic control approach to allow communication, negotiation, and cooperative decision-making to fulfill multiple objectives, even under adverse situations or with disturbances, although only the alteration of an initial ordered quantity and machine malfunctioning are finally considered. Interoperability is important in this cooperative environment, which is why communication protocols follow a specific undetailed ontology. The research by Zhu and Roy (2015) addresses an information framework for disassembly planning processes based on a computational model supported by an ontology-based information model (semantics and domain rules). It addresses one of the main obstacles to develop an optimal disassembly planning system, the uncertain information about product characteristics, e.g., quality and quantity of components and parts; which usually makes deterministic planning of the disassembly process impossible. In Qu et al. (2016), a learning-based dynamic scheduling system for a small-scale multistage, multimachine and multiproduct type job-shop is developed. In this research, three of the usual deterministic JSSP assumptions are relaxed by introducing a more realistic stage: jobs arrive at different times, setup times are sequence-dependent, and machines can be idle while awaiting work. The article's purely ontological content provides very few details. The model proposed by Xue et al. (2017) presents a rescheduling method that adjusts the work sequences of the initial schedule solution with partial or complete rescheduling, whose selection depends on the type of dynamic event that disturbs the system: random job arrivals or machine breakdowns. The model integrates an ontological module that semantically describes the state of the entities and their relationships, and allows stored information to be consulted and modified. The objective of Barenji and Li (2019) is to improve flexible assembly line system performance by implementing a distributed multi-agent system based on radio frequency identification. The model is implemented using the simulation of machines subject to disturbances, while the development of the ontology is limited to the facilitation of communications in the environment. The article by Saeidlou et al. (2019) develops a decentralized multi-agent scheduling system that deals with disturbances like rush jobs and delays and employs an ontology and a reasoner in each agent. Decision-making is carried out with a simple indexing algorithm distributed in each job agent, and a reindexing algorithm in the manufacturer's agent. Peng et al. (2020) present a model of deterministic JSSP based on ontologies with which it intends to, first, summarize the experience and professional knowledge in this domain and, second, integrate learning algorithms based on classification and regression trees (CART) to obtain decision classification rules and class association rules. With them, a library of dynamic scheduling rules is built by finally using this knowledge to carry out scheduling optimization. Unlike the other contributions analyzed in this literature review, that offered by Mabkhot et al. (2020) does not address the job-shop scheduling process but presents an ontology-based decision support system to assist decision makers with flexible manufacturing systems reconfiguration as part of a strategy to react to those disturbances that impact ongoing production, which are identified and classified. Chen et al. (2021) proposes a steel production scheduling system using a hyper-heuristic algorithm based on genetic programming in which, to compensate its dynamic programming difficulty, it proposes an ontology-based scheduling knowledge model and the knowledge representation of ontological attributes, to manage and generate heuristic rules and to solve scheduling problems based on different production perturbations. The research of Li & Tang (2021) addresses the high uncertainty in the scheduling of a customized manufacturing shop floor, where product release date, processing time and machine breakdowns are stochastic and not known in advance. In this case, ontological modeling arises from having to semantically describe the specific customized manufacturing context. Finally, the approach of Saeidlou et al. (2021) is based on the model provided by Saeidlou et al. (2019) to support decentralized scheduling where conflict scenarios, motivated by several production disturbances like job cancellation, manufacturer collapse (zero-processing times), operation delay and rush operation, are posed to test the decentralized scheduling system's resilience. Ontology web language and disjunctive constraints are destined mainly to effectively use the cloud infrastructure.

In addition to the above, the research found in the literature about ontological engineering is also considered relevant, specifically that which corresponds to its confluence with the job scheduling process in the manufacturing domain. In this case, the search for journal articles and conference papers in English in the Scopus and Web of Science databases, and involve the four concepts "manufacturing", "schedul*", "sequenc*", and "ontology engineering", provided two additional results, which are listed in **Table 2**.

Table 2. Literature related to ontological engineering of scheduling process

	Author	Title
1	Cheeseman et al., 2005	Adaptive manufacturing scheduling: A flexible and configurable agent-based prototype
2	Arsovski et al., 2009	The integrating role of simulation in modern manufacturing planning and scheduling

The research by Cheeseman et al. (2005) develops an agent-based manufacturing scheduling system supported by an XML ontology and a message-passing system based on the contract-net protocol, designed to be generic, which allows it to be adapted to a wide variety of manufacturing problems and constitutes a significant advantage. The research of Arsovski et al. (2009) provides a verbal and mathematical description of the scheduling problem, builds an ontology of the problem domain, and uses extended Petri nets, event graphs and activity cycle diagrams as modeling tools to obtain a faithful model that can be easily replicated in an object-oriented hierarchy of classes and objects. Such an approach intends to concentrate comprehensive, but static knowledge, of the ERP into dynamic simulation models and fully utilizes the predictive power of simulation for effective and integrated strategic and tactical decision-making levels.

In short, it is possible to observe from all the aforementioned literature contributions that ontological discourse lies in the production environment domain or the communications of such an environment and is, in most cases, applied as an auxiliary or accessory instrument to support what is actually the main purpose of each article. Therefore, basic information is acquired about how the academic community contributes content to the semantic field of scheduling in manufacturing environments subject to stochasticity, uncertainty, randomness, disturbances, or disruptions, but without generally providing the structure, patterns or relationships on which to build the ontological edifice. On the contrary, (i) the researchs of Peng et al. (2020), Cheeseman et al. (2005), and Arsovski et al. (2009) differ from others in this respect by jointly providing an ontological model which, despite starting from an eminently deterministic model, constitutes a relatively complete basis of the domain defined by JSSP; and (ii) the research of Mabkhot et al. (2020) offers an ontological model which, despite focusing on the domain of reconfigurations of manufacturing environments, which differs from that of the present research, initially addresses its possible disturbances.

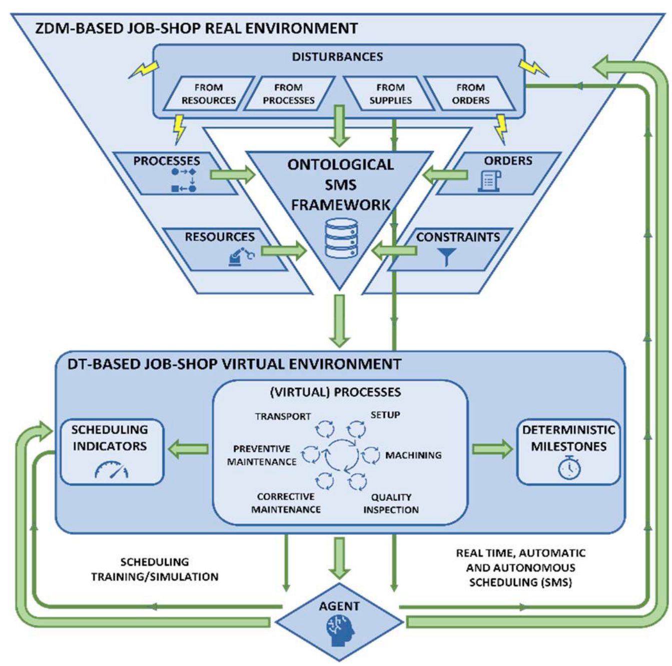

Figure 1: SMS domain setup supported by ontological framework and based on digital twinning

3. ONTOLOGICAL FRAMEWORK

A domain ontology constitutes an intellectual and structured representation of both the entities integrating a specific conceptual space and the existing relationships between them. One of the ontological aspirations is to manage the vocabulary of this conceptual space to consolidate it and to ensure lack of ambiguity. This allows the meaning of each term to always be the same, regardless of its use and user. In the industrial production technological context, this intention comes close to the philosophy that lies behind the ZDM model: minimize the number of defects and errors, and do things right the first time (Wang, 2019), in this case to minimize the number of defects and semantic errors; and properly use the ontological knowledge of the domain from the beginning, to avoid these errors and defects propagating and impacting other processes or systems in the industrial environment, and altering or even interrupting it. The automation and autonomy of the scheduling process, which SMS aims to achieve, require this approach to gain robustness. The real-time management, automation and autonomy of the scheduling process ambitioned by SMS require full digitization to enable quick and efficient analysis, simulation and decision making. Job-shop scheduling virtualization through the digital twin (DT) technology responds to this need (Serrano-Ruiz et al., 2021a, Serrano-Ruiz et al., 2021c). The overall conceptual approach that outlines the domain is depicted in Figure 1.

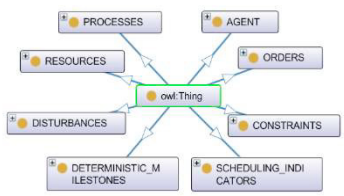

Figure 2: Classes established within the ontological framework (Protégé's Ontograf tab)

The initial ontological framework addressed by this research is conceived as a hybrid approach that can be considered to be partially integrated by elements of three ontologies, namely those related to: JSSP domains, stochastic job-shop casuistry and decision support systems (DSS). The framework is developed in OWL/XML syntax through ontology editor Protégé v.5.5.0 and is mainly structured on three levels: (i) first, the entities constituting the ontology are grouped into classes; (ii) entities present attributes that characterize them as individuals; (iii) entities show properties that distinguish them in their interaction with the other entities composing the ontology framework. By merging these levels, the ontological basis that allows the correct definition of the individuals forming the domain ontology is established.

Within the proposed framework, eight classes are established (offered in alphabetical order): (i) agent; (ii) constraints; (iii) deterministic milestones; (iv) disturbances; (v) orders; (vi) processes; (vii) resources; (viii) scheduling indicators (Figure 2). These classes are further divided into subclasses (Figure 3).

The attributes present in the ontology that allow individuals' characterization are offered in Figure 4. Each attribute at least requires the definition of domain (class/subclass of application) and range. It is advisable to include equivalences to enable the profound use of the integrated reasoner (the indicated version of Protégé incorporates the HermiT reasoner) and to infer the best possible knowledge to the ontology. This figure also details the possible relationships between entities (class/subclass). Here, again, at least the definition of domain and range is required.

According to this basis, the definition of individuals is possible. An example of a hypothetical set of individuals is shown in Figure 5. Obviously, the particular characteristics of each job-shop environment configure a singular set of individuals because the number of individuals of the same type will change: number of machines, number of orders in the process, tasks that each order comprises, etc. The level of required or intended globality for SMS is also critical in terms of the uniqueness denoted by the set of individuals, *e.g.,* not integrating into modeling the alterations caused by machine breakdowns or detections of faulty tools renders considering individuals for machines' corrective maintenance unnecessary.

Figure 3: Classes and Subclasses

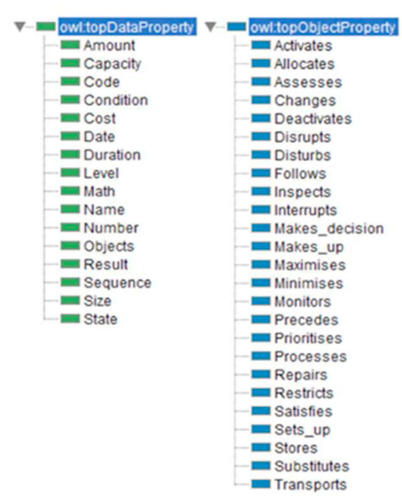

Figure 4: Entities' attributes (on the left) and relationships between the entities (on the right) of the ontological framework

4. DISCUSSION

In the industrial production context, an optimal revenue stream requires a shop floor to operate with its active resources at full load and in a permanent regime. This is not the case when activity reduces, regardless of the cause or, worse, when it is interrupted. Accordingly, job-shop scheduling efficiency is a key issue, and has been extensively studied by the scientific community as such. No less important is the effect of the disruptions that unexpected events can have on shop floor activity, an issue that has also been well-researched. A third and less addressed approach is that of the shop floor response time when unexpected events occur, such as arrivals of new orders or machine breakdowns. This aspect is crucial for productivity, but its approach significantly differs depending on the time approach followed for the scheduling process: (i) in the classic approach, where static schedules are calculated for the orders in the backlog and are revitalized by their recalculation (rescheduling) every time a change cancels their validity, not only the response time is important to obtain the new schedule. As a temporally discontinuous process, in this scheduling approach both frequency of rescheduling and the ideal time to launch it are also determining factors to keep productivity and costs within acceptable ranges (Psarommatis et al., 2020); (ii) on the contrary, when the approach applied to the scheduling function involves a continuous and adaptive process, and in real-time synchrony with shop floor operations and, as far as possible, also with its stochasticity, the response time is critical because its intentions is to cancel it, or more precisely, reduce it to make it imperceptible at the time scale level that governs shop floor operations and to, thus, maintain synchrony. With this second approach, the rescheduling concept also changes: in the classic approach, each rescheduling is assumed to be a punctual correction of the current schedule and is, therefore, taken as a discontinuity whose impact propagates to resources and processes. However, for a real-time synchronized scheduling system, rescheduling is essentially normal as it occurs continuously and automatically in synchrony with production processes (Serrano-Ruiz et al., 2021c). In such an environment, the scheduling process plays the role of a critical resource as scheduling failure can lead to the production system on the whole to fail (Fang et al., 2019). Consequently, it is necessary to identify and manage the underlying causes of possible failures, such as unexpected events, abnormal disturbances, or information asymmetries (Fang et al., 2019).

The proposed ontological framework responds to the needs raised in this regard in the initial SMS modeling stages. On the one hand, its structure includes a specific class which collects the main disturbances that can be detected and identified in job-shop environments. On the other hand, the ontological editor allows: (i) to declare the characteristics of each job-shop domain element *per se*; (ii) the characteristics that define the interrelationships between these elements; (iii) the characteristics defining the relationships between these elements and the identified sources of disturbance; and (iv) infer additional properties with the integrated reasoner which, all together, act as a means to prevent possible information asymmetries, especially in complex SMS environments. Detection and prevention are two of the four ZDM strategies (Psarommatis et al., 2020). So, it is reasonable to think about domain ontologies as being a valuable ally of the zero-defect philosophy in pre-modeling stages.

It can be stated that using ontologies offers an indirect advantage of facilitating the implementation of scheduling frameworks for distributed production environments in which decentralized and autonomous decision making occurs as it paves the way towards the interoperability required when working in environments based on cloud manufacturing systems (Mezgár and Rauschecker, 2014).

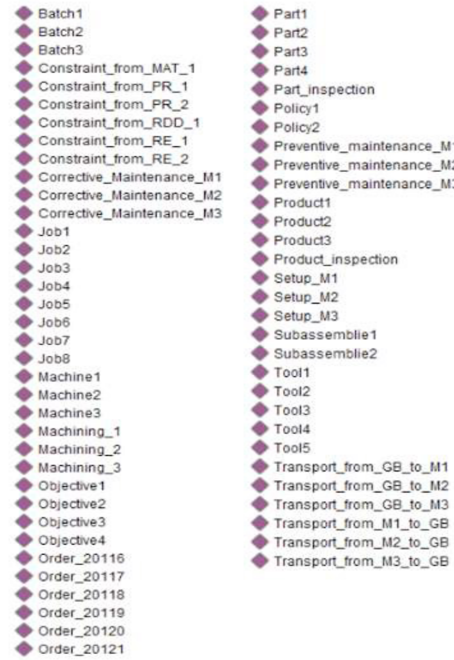

Figure 5: Example of a hypothetical individuals set

Regarding the real-time rescheduling problem, it should be noted that digitization support is necessary for rapidly and efficiently enabling tools like analysis, simulation and decision making to avoid the scheduling process ending up like another source of uncertainty, which can alter job-shop dynamics and reduce its productivity. Implementing DT technology can help with this endeavor by generating a virtual replica of the process (Jones et al., 2020; Kritzinger et al., 2018).

So, the combination of ontology, ZDM and DT is believed beneficial by fulfilling SMS objectives. Nevertheless, we clash with the complication of modeling the usually non-deterministic polynomial-time (NP-hard) JSSP, a difficult task in itself, significantly increases by adding both stochastic terms to the objective function and stochastic constraints. The same applies to solution methods. The more effective method of classic ones, such as simulation methods, on the one hand, or heuristics, metaheuristics and matheuristics algorithms on the other hand, get into trouble from a resolution time perspective (Shahzad and Mebarki, 2012) beyond the second or third stochastic term in the problem modeling. This reality leads us to machine-learning technologies, such as deep reinforcement learning, deep Q network or even hyperheuristics (Lara-Cárdenas et al., 2020), as possible solution alternatives.

6. CONCLUSIONS

This research provides an overview of the current state of the art of ontological approaches applied to the stochastic JSSP domain and presents an initial ontological framework for SMS that can be used as a semantic basis for modeling. The main findings are summarized as five: (i) the proposed ontological framework helps to prevent information asymmetries in SMS environments; (ii) the adopted ontological approach aligns with the ZDM strategy; (iii) using ontologies favors the interoperability of scheduling distributed production environments; (iv) supporting DT technology in combination with the proposed ontological framework orients SMS systems toward their real-time operation; and (v) the difficulty of the problem implied by SMS problems makes machine-learning technologies alternatives to solve them. From the academic point of view, this research sets a precedent to gain a more in-depth understanding of the topic, which will facilitate future SMS modeling research.

The validation of the proposed ontological framework with the design of experiments, or the development of a case study, would overcome the limitation of the conceptual approach in this research, by constituting a future research line to be highlighted. In any case, the difficulty of modeling stochastic JSSP from a holistic perspective that addresses all the sources of uncertainty considered in this ontological framework, and that directs scheduling toward its automation and autonomy in time synchrony with workshop processes, is a huge problem with considerable complexity, which will surely oblige a step-by-step methodology to be followed for its development, based on the stepwise incorporation of each stochastic term in the SMS modeling and experimentation phases. This task should also be considered another research line.

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