ERC Advanced Grant 2017
Research proposal [Part B2]

White-Box Self-Programming Mechanisms

WhiteMech

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– Proposal duration: **60 months**

Contents

This part of the proposal should be read in conjunction with Part B1, which is to be considered an integral part of the project description.

a State-of-the-art and objectives

a.1 Motivation

We are witnessing an increasing availability of **mechanisms** that offer some form of programmability. Obvious examples are software in our computers and mobile devices, as well as intelligent machines, such as cognitive robots, self-driving cars, flying drones, etc., which are becoming a reality. In particular, programmable mechanisms are increasingly becoming important in three contexts considered of pivotal importance in today's economy, namely **Manufacturing**, **Internet of Things**, and **Business Process Management**. These three areas will act as specific testbeds for the science and technology developed within WHITEMECH.

There are compelling reasons to introduce **self-programming abilities** in these systems, such as **self-adaptability** to changing users and environment conditions exploiting information gathered at runtime [162], and **automated exception handling** to suitably **recover from unexpected situations** [134]. The current technology, e.g., **autonomic computing**, which has long advocated self-configuration, self-healing, self-optimization, and self-protection, however, is essentially based on **preprogrammed solutions** by IT professionals [112]. That is, although sophisticated languages and methodologies for streamlining the development of adaptation and exception handling recovery procedures are available, IT professionals, software engineers and programmers, are still writing all the code by hand. As a result, in spite of the progress in the organization of the software development process, this traditional way of tackling automated reactions in mechanisms is showing serious limitations. In many application areas, it is simply too **costly** and **error-prone** to delegate to software engineers to list and handle all possible adaptation tasks that may arise in the mechanism execution. In fact, especially when applications have to handle widely unexpected circumstances, stemming from the interaction with the real world or with humans taking decisions based on unmodeled circumstances, as indeed in Smart Manufacturing, Internet of Things and Business Processes Management, it is considered simply **infeasible** to determine apriori all possible adaptations that may be needed at runtime [134].

In this state of affairs, the fantastic progress in Machine Learning that we have seen in recent years is attracting a lot of attention. **Machine Learning** is a powerful tool to avoid **preprogrammed solutions** in favor of **learned solutions**, and there are indeed great and fully justified expectations of what machine learning can bring about in relieving humans from having to preprogram mundane adaptation tasks.

However, in machine learning, we typically don't have an undestanding of how and why a certain solution has been chosen. This **lack of understandability of machine learning solutions** is increasingly becoming a concern in both the AI and CS scientific communities, [154, 1], and has been recently taken up by DARPA, through the DARPA-BAA-16-53 "Explainable Artificial Intelligence (XAI)" program.[1] For example, the ACM Statement on Algorithmic Transparency and Accountability [1] says: "*There is also growing evidence that some algorithms and analytics can be opaque, making it impossible to determine when their outputs may be biased or erroneous.*"

Beyond the opaqueness of machine-learning-produced solutions, there are also widespread concerns about the **safety** of using such solutions and whether they are thrustworthy.[2] For any system that operates autonomously, there must be guarantees that suitable safety constraints will always be respected. The relevant safety constraints must be specified in a language that human users understand. The system must be able to explain its decisions so that human users can understand the system's operation and confirm that it does follow the relevant rules of conduct. This is crucial for building users' **trust** in the system.

[1] http://www.darpa.mil/program/explainable-artificial-intelligence

[2] These concerns have been widely discussed, see for example https://futureoflife.org/background/benefits-risks-of-artificial-intelligence/.

Hence on the one hand there is a widespread recognition in the AI and CS communities that the objectives of WHITEMECH, that is, building self-programming mechanisms that are white-box, are very important. On the other hand, we are currently stuck between two extremes: either we provide preprogrammed solutions, but this is not cost-effective or even feasible for certain applications, or we use machine learning to produce solutions, but this often means that we give up transparency and accountability, and ultimately human comprehensibility.

WHITEMECH aims at addressing the realization of white-box self-programming mechanisms on **radically different bases**. It will leverage **Reasoning about Action** and **Generalized Planning** in AI, which provide the explicit representation required for being white-box and the automated synthesis techniques required for self-programming. However traditional Reasoning about Action and Planning are by far too simple to be used off-the-shelf for realizing white-box self-programming mechanisms. So **WhiteMech intends to revolutionize them by introducing rich objectives, semantically characterized data, and componentization.** To do so, WHITEMECH will take elements from **Verification and Synthesis** in Formal Methods and **Data-aware Processes** in Databases, and combine insights from the four areas in a novel way to get the right balance between power and effectiveness. Table 1 summarizes which areas contribute to which WHITEMECH's objectives (cf. B1).

Table 1: Areas and WHITEMECH objectives.

	Objective 1	Objective 2	Objective 3	Objective 4	Objective 5
Generalized Planning	✓	✓			✓
Verification and Synthesis	✓	✓		✓	✓
Reasoning about Action		✓	✓		
Data-Aware Processes		✓	✓		

Below we go over each WHITEMECH objective, describing the relevant state-of-the-art and the key ideas for addressing the associated challenges.

a.2 Objective 1: Equip mechanisms with general self-programming abilities

a.2.1 Generalized Planning

Self-programmability is essentially the ability of a mechanism to adapt to new, unexpected conditions, while still being able to achieve its goals. In this view, self-programmability requires that a mechanism be able to produce a plan or a strategy that achieves a desired goal, every time conditions change. In other words, the mechanisms must be able to **plan for a goal**. WHITEMECH will investigate an approach based on Planning in AI as a starting point to obtain self-programmability.

Planning is a branch of AI that addresses the problem of generating a course of action to achieve a desired goal, given a description of the domain of interest and its initial state. The area is central to the development of intelligent agents and autonomous robots. Within WHITEMECH, the planning paradigm provides a valuable set of theoretical and practical tools to tackle self-programming: as conditions change, a mechanism can simply build new plans for the desired goals. This can be done very efficiently; indeed, in the last decades, Planning has seen spectacular progresses in terms of scalability, through the use of heuristic search and symbolic approaches [100, 103]. One aspect of Planning in AI that is crucial in WHITEMECH, is that **goals are dynamic**, that is, goals are produced continuously, as the agent operates. However, while in Planning a plan for the next goal must be built only after the current goal is achieved, mechanisms have the option to drop the current goal or combine it with the next one, thus adding a complication that cannot be dealt with straightforwardly by standard Planning techniques.

In Planning, the domain where a mechanism operates is described by a set of atomic facts, called *fluents*, and by a set of *actions*, each described by preconditions and effects. In a state, only actions whose preconditions are fulfilled can be executed. The execution of an action yields changes to the truth value of fluents, which, in turn, lead the domain to a new state. This is the reference *Model* of Planning, over which a mechanism can reason to come up with a successful plan. Such model, coming

directly from **Reasoning about Action** in KR [148], is, e.g., embedded in the de-facto standard Planning Domain Definition Language (PDDL) [138, 102].

Planning models have a number of important features for WHITEMECH. Firstly, they are **human-comprehensible**, in that fluents and actions describe the domain of interest in a high-level terminology, readily accessible to humans. Secondly, they constitute implicit representations of finite-state transition systems, and are thus readily **queryable by standard verification techniques**, such as *Model Checking*[59, 16, 132], which typically operate on finite-state systems. By incorporating these features in a mechanism model, **WhiteMech will retain both human-comprehensibility and model verifiability.**

Further, Planning offers the possibility of formulating *Explanations* [27, 167, 160, 152, 126, 183, 96]. The crucial point is that Planning being based on models, explanations can be generated from queries over the planning domain and the plan itself. These queries are essentially based on verification tasks (though they might involve costs and other parameters), of both linear-time and branching-time (to look at alternatives) properties. **WhiteMech will retain the possibility of querying the model.** Furthermore, WHITEMECH will lay the fundations to perform a **what-if analysis** (i.e., querying the behavior of the mechanism/plan under different circumstances to understand its robustness) by checking properties of interest after placing constraints on the domain as well as on the adversary strategy of the environment where the mechanism acts in.

Unfortunately, although Planning embeds properties desirable for WHITEMECH, it cannot be adopted off-the-shelf to achieve self-programmability, as **traditional Planning models are too coarse to capture important mechanism features**, such as *relational data manipulation* or *componentization*. To address the former, WHITEMECH will introduce **rich semantic descriptions** from Knowledge Representation, to which the *PI has contributed significantly over the years [78, 67, 73, 157, 158, 72, 68, 70, 71, 19]*; in this way, mechanisms will be specifiable which incorporate relational data manipulation capabilities, thus **lifting models to a first-order state representation** (cf. Objective 3). To address the latter **componentization will be incorporated in WhiteMech**: as typical of Service-Oriented Computing [32, 168, 26, 77, 64], mechanisms will consist of several components, suitably coordinated and orchestrated, each with its own features (cf. Objective 4). *The PI has pioneered work on composition of stateful-services (services that react depending on the state there are in) [24, 23] and later extended these results to handle behavior compositions, e.g. of cognitive robotics systems in AI [155, 156, 77, 64].*

Also the **goal specification formalism of traditional Planning is too limited for mechanisms**. In Planning, goals are specified by boolean combinations of fluents and are considered fulfilled by a plan when a state is reached that satisfies the boolean combination. WHITEMECH, instead, aims at handling full-fledged temporal specifications analogous to those used in model checking and reactive synthesis [59, 16, 142], but mainly over a finite time-horizon. For this reason, WHITEMECH will adopt non-traditional specification formalisms, such as *LTL and LDL on finite traces, recently proposed by the PI together with Moshe Vardi (Rice U., USA) [82, 79, 80] and adopted in generalized forms of Planning in AI [173, 50] and in declarative business processes in BPM [175, 60, 74]*, or safe/co-safe LTL/LDL formulas, which have been shown to be more expressive than expected, while remaning **well-behaved** [94, 93, 125, 91]. Indeed, these formalisms allow us to sidestep the notorious difficulties encountered when dealing with their infinite-horizon counterparts. Solvers for these are indeed substantially simpler that those for general reactive synthesis, as they are based on reachability and safety games, which are amenable to efficient implementations. Importantly, the new formalisms adopted in WHITEMECH **will retain the human-comprehensibility featured by traditional goals**.

Planning comes in a variety of forms, each designed to capture certain domain features. In **Classical Planning**, where actions are deterministic and plans are action sequences, finding a plan that, from the initial state, leads the domain to a state satisfying the goal is a PSPACE-complete (reachability) problem. In **Nondeterministic Planning**, instead, actions are nondeterministic and a solution is a function, known as a *policy*, which returns the action to execute, given the current state (a policy is in fact a strategy, which can be memoryless in these problems). Nondeterministic Planning is further divided, based on whether the agent can or cannot observe all of the features characterizing the state, into **Fully observable (FOND)**, which is EXPTIME-complete in the domain description,

and **Partially observable (POND)**, which is 2EXPTIME-complete, cf. [150]. All of these variants have been, and currently are, deeply investigated, compared and solved by the Planning community, which has devised numerous solution strategies, then implemented, tested and optimized in actual planners. The results achieved include, to mention some: advances in FOND planning that have greatly improved the efficiency in this setting [124, 135, 99, 117, 140]; early POND planners, such as CNLP [141], Cassandra [145], and Graphplan (e.g., SGP [7]); model-checking-based planners, such as MBP [25] and BBSP [151]; planners based on heuristic search, such as Contingent-FF [108], "POND" [37], and the more recent CLG [2, 3, 31].

These efforts, over several decades, have led to the development of a sort of **science of search algorithms for Planning**, which has allowed us to confine the inherent complexity of Planning within a set of hard instances, while keeping most cases of practical interest efficiently solvable [144, 169, 131, 74]. Since we expect mechanisms to require, in most cases, solving non-puzzle-like problems from well-behaved classes, WHITEMECH will exploit the body of knowledge built in decades of research in Planning and will extend algorithms and heuristics to handle generalized forms of Planning. In particular, recent work by the **PI has explored connections between generalized forms of Planning and Synthesis** when goals are temporally extended: goals are expressed as requirements on the entire execution instead of the final state of the execution [114, 13, 53, 81, 14, 49]. *Promising exploratory results by the PI and other [63, 159, 82, 79, 50] are available*, but such results do not yet fully clarify the picture both from a theoretical perspective and from an algorithmic perspective. Nonetheless, it appears possible to **compile** the more general forms of synthesis problems which reduce to reachability and co-reachability/safety games **into synthetic planning domains so as to exploit the algorithmic insights from Planning**, i.e., Classical Planning, FOND and POND, to efficiently solve these games. In particular, it appears possible to exploit the correspondence between FOND and 2-player games, and the significant recent advances in the computational efficiency of FOND planning that have produced FOND planners that scale well in many domains (e.g., NDP [4], FIP [99, 98], MyND [135], Gamer [117] and PRP [140]).

The crucial point of the approach is that Planning-based solvers embed very effective domain-independent heuristics, continuously improved by a dedicated scientific community. Importantly, no specific modeling formalism is needed to take advantage of the advances, and to obtain such efficiency [97]. Hence, in spite of the notable changes in the model and the goals that WHITEMECH will introduce, **we expect that the planning algorithms employed will scale up** as they do in standard Planning.

a.2.2 Verification and Synthesis

Apart from Planning, WHITEMECH will draw on the rich modeling and algorithmic techniques from Formal Methods, particularly Verification and Synthesis.

The main approach to program verification is **model checking**. This is the problem of automatically determining whether a system model satisfies a formal specification expressed in logic [59, 16]. This field, for which the founders and proponents won two different Turing awards, has been used successfully for complex systems, and many hardware and software companies use this approach in practice for, e.g., verification of VLSI circuits, communication protocols, software device drivers, real-time embedded systems, or security algorithms.

The same community has been developing **synthesis**, i.e., an approach to automatically construct a system that satisfies a given specification. Of particular relevance is synthesis applied to reactive systems: those that maintain an ongoing interaction with an external environment.[3] Such **reactive synthesis** is best viewed as a game between the uncontrollable environment and the program to be synthesized. A correct program can then be viewed as a winning strategy in this game, and thus synthesis reduces to finding such a strategy [57, 142]. Over the years, the formal-methods community has exploited this game-theoretic viewpoint and developed a **comprehensive and mathematically elegant theory of reactive synthesis** connecting logics, automata theory and games [177, 122, 123, 121, 178, 105, 55, 29, 30, 94, 133, 95, 101, 92, 28, 6, 90, 36, 111].

In spite of the rich theory developed for reactive synthesis, little of this theory has been adopted in practice. Some researchers argue that this is due to the computational complexity of the realizability

[3] This is in contrast to classical non-reactive programs that transform static inputs into static outputs.

problem, e.g., 2EXPTIME-complete for LTL [142, 153]. However, this argument is not compelling. First, experience with verification shows that even nonelementary algorithms can be practical, since the worst-case complexity does not arise often (cf., the model-checking tool MONA [89]). Furthermore, in some sense, synthesis is not harder than verification. This may seem to contradict the known fact that while verification is linear in the size of the model and at most exponential in the size of the specification [59], synthesis from LTL specifications is 2EXPTIME-complete. There is, however, something misleading in this claim: while the complexity of synthesis is given with respect to the specification only, the complexity of verification is given with respect to the specification and the program, which can be much larger than the specification. In particular, it is shown in [153] that there are temporal specifications for which every realizing program must be at least doubly exponentially larger than the specifications. Clearly, the verification of such programs is doubly exponential in the specification, just as the cost of synthesis.

Nonetheless, there are a number of reasons for the **lack of practical impact of the theory of reactive synthesis**. We list 3 of these, and include principles and directions for overcoming them within WHITEMECH.

(i) **Combining the representation of the task and the model into a single specification, (e.g., expressed in LTL) hides the relevant complexities**. Exactly as in model checking, we need to distinguish the **complexity wrt the model of the mechanisms** and the **complexity wrt the specification of its tasks (goals)**. In this light, the complexity of solving games with LTL objectives is PTIME-complete in the size of the model, i.e., EXPTIME-complete in the compact representation of the model, and 2EXPTIME-complete in the size of the specification formula of the goal. Thus, even in the case that the model is given compactly (as in Planning), the complexity wrt the model is much lower than the complexity wrt the specification. This is a particularly important observation, since in general the model is going to be much larger than the goals. **WhiteMech will exploit this important distinction.**

(ii) **The specification languages lead to constructions that are too complex**. The approach to LTL synthesis or solving LTL games involves two main steps. First, constructing parity tree-automata that realize all winning strategies, and second, testing such automata for emptiness. The first step can be done using determinization of Büchi automata. Unfortunately, determinization of these automata is not as simple as determinization of ordinary automata (on finite strings), and has been notoriously resistant to efficient implementations [174]. Alternative constructions that avoid determinization [123, 121] did not prove to be radically more efficient [93]. The second step involves solving parity games. This problem, solvable in quasi-polynomial time, is not known to be in PTIME [38] and has been attacked with many different algorithms.[4] However, as mentioned, there are relevant classes of specifications, coming from generalized planning in AI and declarative business processes, which **sidestep these difficulties altogether**, i.e., linear-temporal logics over **finite traces**, such as LTL_f and its MSO-complete extension LDL_f. The principal technical advantage of using these is that they involve *ordinary* automata on finite words which are indeed amenable to quite good implementations [175, 82, 79, 80, 173, 50]. **WhiteMech will build upon these well-behaved classes of specifications.**

(iii) **Techniques are optimized for solving difficult synthesis problems, including puzzle-like ones**. Reactive synthesis is typically applied to low-level problems in which there is no reason to think that solutions are easy to find (the Planning literature calls these "puzzle-like problems"). On the other hand, we expect mechanisms to require, in most cases, solving problems from well-behaved classes, i.e., large problems that are not "puzzle-like". Following this assumption, Planning has obtained a spectacular improvement in the last two decades, relying on heuristics which ultimately can be seen as abstractions/approximations that relax details of the problem at hand. **WhiteMech will apply such heuristics to synthesis**. WHITEMECH will also explore new techniques from the formal-methods community, such as those for bounded-synthesis where small controllers are explored before large ones [94, 93, 91], which appear to be quite promising [113].

Finally, we mention that in Verification and Synthesis, **parallel solvers for synthesis games** based on a domain decomposition approach have been recently developed [10, 11]. The general principle is

[4] See, e.g., https://github.com/tcsprojects/pgsolver.

this: partition the problem into sub-problems to be solved in parallel, and then efficiently combine their solutions to get the one for the original problem. Benchmarks on random games have proved the usefulness of this idea when applied to the Zielonka Algorithm [181] for parity games, both in terms of computational cost and of scalability. Specifically, this work shows an improvement factor linearly dependent on the number of cores used and an irrelevant communication overhead among the executed processes. **WhiteMech intends to explore the potential benefits offered by parallel algorithms.** This will be done in *collaboration with Camil Demetrescu at Sapienza and Nello Murano at U. Naples.*

a.3 Objective 2: Make self-programming mechanisms comprehensible and verifiable by humans

The third ingredient of the WHITEMECH approach is **Knowledge Representation**, in particular **Reasoning about Action**. The key property of white-box self-programming mechanisms is the ability to describe the domain in which they operate, their specification, the programs they generate and the relationship between the two in human terms. To do so, the domain where the mechanism operates, the mechanism itself, its capabilities and limitations, as well as its specifications and goals, need to be formally described in terms of concepts that are comprehensible by humans. WHITEMECH will consider this issue upfront, by founding white-box self-programming mechanisms on the area of AI called **Knowledge Representation**.

The PI is a prominent member of the scientific community working on Knowledge Representation. He is indeed the single researcher with the most papers in the flagship conference of the community: the International Conference on Principles of Knowledge Representation and Reasoning (KR), ranked A according to CORE.*

Knowledge Representation stems from a long tradition in logic, which aims at building systems that know about the world they operate in and are able to act in an informed way, just as humans do. A crucial feature of these systems is that knowledge is represented "*symbolically*" and that "*reasoning procedures*" are able to extract consequences of such knowledge as new symbolic representations. Such an ability is used to deliberate in an informed fashion over the course of action to take, understanding the consequences of the actions performed. Knowledge Representation has developed enormously since its origins in diverse directions and subareas [136, 127, 128]. Within WHITEMECH we focus mainly on the areas of Reasoning about Action and Description Logics.

Reasoning about Action takes a first-person view of an agent.[5] The agent has: a representation of the domain in which it operates; a representation of the possible actions in terms of preconditions and effects formally expressed over the representation of the domain; and a representation of complex agent behaviors and capabilities, typically described through high-level programs, whose atomic instructions and tests correspond, respectively, to actions and queries over the representation of the domain. By reasoning over these representations, the agent understands what an action or behavior will bring about, thus gaining the ability to make informed decisions on which action to choose or to exclude in relation to its current tasks/goals/specifications. Reasoning about Action has been studied in depth through comprehensive frameworks, such as that of Situation Calculus [137, 148]. As mentioned, it has provided the bases for the models used in Planning, including PDDL.

The PI has deeply contributed to the development of Reasoning about Action, especially within the framework of Situation Calculus, by introducing: the high-level programming languages ConGolog and IndiGolog; the distinction between off-line and online execution; the notion of execution monitoring and recovery; the idea of interleaving execution and planning; and the notion of ability [78, 67, 157, 158].

Importantly, this work in the Situation Calculus, as well as in many other frameworks, is based on a **First-Order Representation of the State**: the state of the agent is represented in terms of predicates/relations. This gives rise to infinite-state transition systems which are typically impossible to verify directly. *Recently, the PI has devised a set of novel results showing the effective computability of expressive variants of the original full-fledged (predicate based) Situation Calculus [70, 71, 69, 19,*

[5] This contrasts with the work in Multi-Agents Systems, where typically a third person view (a "designer" view) is adopted.

47]. Moreover, the techniques for applying belief revision to transition systems proposed in [107, 51], open up the possibility of grounding computationally the notion of "model revision" for mechanisms.

WHITEMECH intends to represent the state of mechanisms as well as the state of the enviroment in a semantically rich fashion. To do so we will rely on Description Logic and Ontology-Based Data Access.

Description Logics are the formalism of choice for representing information about the domain of interest in terms of objects grouped in classes or concepts and relationships among such classes. Moreover Description Logics are nowadays considered the standard formalism for ontologies and semantic technologies, cf. the W3C standard OWL 2.

The PI has strongly contributed in the development of Description Logics. He first worked on the correspondence between expressive Description Logics and Modal Logics of programs, such as Dynamic Logic [66, 42]. More recently, together with his group in Rome, he developed one of the best known light-weight Description Logics, DL-lite [40], which is essentially able to formalize UML class diagrams and Entity-Relationship diagrams, while keeping inference and conjunctive query answering tractable (the latter in AC^0, the same complexity as standard SQL). DL-lite, in turn, made it possible to develop ***Ontology Based Data Access****, which can be considered the most successful use of semantic technologies for Data Integration [143, 164, 115].*

The role of these technologies in WHITEMECH is to represent in terms of an ontology the doman of interest in which the mechanism is operating, as well as the mechanism itself in terms that are human-comprehensible as done, e.g., in [171]. Technically such ontologies act as so called state-constraints, i.e., assertions that must hold in every state, which are notoriously problematic do deal with [130, 148]. However *the PI has recently studied the feasibility of combining action theories with ontological representations in Description Logics [43, 41, 106, 48].* WHITEMECH intends to exploit these results, while profit form efficient query-aswering provided by DL-lite and Ontology-Based Data Access, especially in its write-also variant explored recently [76, 65]. However, WHITEMECH does not aim at defining new concrete representation languages. Instead, it will use well-known formalisms such as BPMN, UML, OWL, etc. as concrete languages, though with a precise formal semantics to allow for automated reasoning, verification and synthesis, see e.g., [22, 75].

a.4 Objective 3: Make self-programming mechanisms data-aware

Differently from current work in Planning and Verification and Synthesis, which adopt a propositional representation of the state, WHITEMECH will not discard relational data, and hence will consider **first-order or relational representations**. Apart from Reasoning about Action, the other area that is looking into this issue is Data-Aware Processes in Databases.

Data-Aware Processes emerged, in the last decade, as an integrated framework to simultaneously capture both the (relational) data of interest in an organizational environment and the (business) processes operating over such data [45]. Traditionally, data and process management have been investigated in mutual isolation, so as to attack the complexity of the organization with the usual *divide et impera* approach. This has led to very successful languages, methods, and approaches in each area, such as UML class diagrams and ER diagrams for data modeling, and BPMN and EPCs for process modeling. However, this isolation fails when one wants to understand the organization as a whole, take informed decisions, and model end-to-end processes by uniformly combining their business logic and the underlying information systems [149, 85, 147]. This is even more critical if one considers that, in the last decade, we have witnessed a progressive shift from traditional repetitive and predictable production processes, to complex and unpredictable knowledge-intensive processes [176, 109, 120].

As a reaction to this trend, a new generation of data-aware process models and execution environments arose, with business artifacts [109] and object-centric approaches [120] as its main representatives. At the same time, a flourishing literature on the foundations of verification for such rich models has been produced, devising a plethora of sophisticated decidability results obtained by fine-tuning the interaction between the process and the relational data component (see [179, 45] for two comprehensive surveys on this challenging topic). The key issue is that relational data in the states gives rise

to infinite-state transition systems which are generally problematic to analyze. *The PI has already shown within the EU FP7-ICT-257593 ACSI: Artifact-Centric Service Interoperation, that such difficulties can be overcome in notable cases [23, 39, 15, 46].* A key discovery is that under natural assumptions these infinite-state transition systems admit faithful **abstractions** as finite-state ones, hence enabling the possibility of using the large body of techniques developed within Verification and Synthesis in Formal Methods. Moreover important advancements in undestanding how to deal with such complexity have been established as well as relationships with Reasoning about Action in KR [106, 21, 48, 47, 19]. By leveraging these ideas WHITEMECH will lift the results so as to handle data.

In this light, WHITEMECH will exploit data-aware processes to obtain a rich, coherent, representation of mechanisms that enjoys two fundamental properties: being amenable to verification, thus paving the way towards automated reasoning; being data-aware, thus making it possible to formulate explanations that simultaneously take into account the specification of the process and the application context. At the same time, WHITEMECH will expand the boundaries of this research areas along two crucial directions. First, while the majority of data-aware process modeling languages depart from standard modeling languages, WHITEMECH will **enrich reference process modeling languages (such as BPMN and variants of Petri nets) with data-related aspects**, building on recent, seminal results [83, 139, 75]. Second, while the vast majority of the literature has mainly focused on modeling and verifying data-aware processes against temporal/dynamic properties of interest, **WhiteMech will develop sophisticated forms of synthesis for data-aware processes**.

a.5 Objective 4: Support component-based approaches

Programmable mechanisms are not necessarily composed of a single unit, but of several components, each described separately in terms of interfaces and possible behaviors. **Service-Oriented Computing** and **Open APIs** frameworks have long been pushing for such **component-based systems**, in which a set of components are **customized** and **orchestrated** to deliver a required service [32]. Indeed, understandability calls for building **high-level components** that are relatively simple to understand, verify and combine. Then, it is crucial to study how **composing** "correct" components leads to an overall "correct" behavior. WHITEMECH will take advantage of the large body of work on composition and customization developed in Service Oriented Computing and more recently in AI [168, 26, 77, 64]. Moreover, execution will be **monitored** so that in case of failure it is possible to identify the responsible component, and recover the situation by reprogramming the mechanism for alternative solutions that circumvent the failing component [60, 134].

Interestingly, most synthesis techniques are not compositional, i.e., they assume that one gets a comprehensive set of temporal assertions as a starting point. This is a major methodological issue. However a quite different approach is that of bounded synthesis [94, 93, 91] in which the LTL formula is first transformed into a coBüchi automaton on trees which is then further reduced to a safety game, given the maximum size of the controller to synthesize. Then the size in incremented iteratively, until a strategy is found or an exponential limit is reached which guarantees that no strategy can be found at all. Notably, safety games allow for defining **maximally permissive nondeterministic strategies** [182, 88]. Thus, based on this, one can define **compositional techniques** in which strategies for single components are computed separately through safety games and then are easily composed [121, 93, 6]. WHITEMECH *will explore these ideas in combination with composition from service-oriented computing pioneered by the PI [24, 63, 77, 44].*

a.6 Objective 5: Integrate stochastic decisions and reinforcement learning

The dynamics and control of many systems is inherently uncertain, and this uncertainty must be taken into account when deploying algorithms that seek to automatically choose adequate behaviors. So far, we discussed nondeterministic models, but **stochastic models are also of interest in WhiteMech**, e.g., to represent components that are developed using machine-learning techniques. Stochastic models enable us to quantify the uncertainty, allowing for more informed risk analysis. Popular models include Markov Decision Processes (MDPs) [146], partially observable MDPs (POMDPs) [52] and stochastic games (SG) [165]. Moreover, some of the algorithms used to address such domains make stochastic choices. For example, Monte-Carlo search algorithms base their choice on stochastic samples

of possible futures [118, 166], reinforcement learning (RL) [170, 180, 35] algorithms often explore the space stochastically, while optimal decisions in adversarial settings often require randomization [129, 56]. Also in these settings, it is important to be able to provide safety guarantees and express clearly the objectives of the system and required properties (such as conformance with regulations).

In the extreme case of an agent acting in an unknown environment, such as an agent faced with a choice between two buttons to press, with no knowledge of the implications of each choice, there is little we can do. But the application domains of WHITEMECH are quite different, as there is usually some understanding of the domain, and hence, an approximate model. What we seek is to improve on manual choices in such domains, and support adaptivity. Thus, even without a model, we can provide the algorithm with **advice** on its action choices. Simple advices can take the form of "*do not use action a in state s*", while more interesting ones may concern long-term behavior, e.g., "*make sure to cool the engine every now and then*" or "*do not touch a pot that has been heated for some time*". Even more interesting advice can take the form of a skeleton for a program, e.g., "*while it is hot, make sure the window is open, and if it does not cool, turn on the air-conditioning*". Note that such advice can be provided without having a complete model in mind.

Even when a model exists, such as in MDPs and POMDPs the ability to express and use such information is crucial. These models specify their objectives using a reward function, i.e., a function that associates a real value with every state of the world, representing how desirable it is. Unfortunately, the standard reward functions do not naturally support the specification of more **complex long term requirements**, such as not operating the system is some mode for long periods of time, or ensuring that requests are ultimately serviced, or seeking to have the solution **conform to some program skeleton**. Some earlier work examined the question of how to enhance these reward function to express more complex, non-Markovian, rewards [12, 172]. *Recently, the PI and co-authors [33, 34] have developed improved techniques for addressing this problem*, which are both more expressive and more efficient. Specifically, one can also describe the above constraints and objectives using the expressive language of LDL_f. Using this language, one can describe program skeletons and long-term behaviors. This allows for **restricting and guiding the behavior of RL algorithms as well as the programs generated by solving MDPs and POMDPs.**

We can use such LDL_f formulas to ensure safety and to provide more careful specifications for the algorithm's behavior. First, we can describe constraints that restrict the exploration of the algorithm to remain within a safe zone. Second, we can specify additional desiderata. For example, while an RL algorithm learns about the rewards associated with diverse, unknown, states of the world and about the world dynamics, we can inject additional, artificial rewards that steer it towards behaviors that satisfy these formulas. This can also be done when solving a known model, as described above: using this language, we can inject additional rewards or constraints that the solution algorithm will either optimize or satisfy. What is most important, is that this can be done efficiently! These formulas can be encoded as finite-state machines that can be used to augment the state space in a way that is transparent to existing algorithms, and typically, quite efficiently. *In on-going work, the PI and co-authors show how these methods can be integrated into classical dynamic programming and search-based methods*, and WHITEMECH will enhance these tools, as well as integrate them with algorithms for learning state machines [8, 9], in order to provide more advanced methods for RL and inverse RL that can take into account such specifications. In summary, **WhiteMech will develop techniques to integrate learning and stochastic decisions, while respecting human-comprehensible safety specifications.**

a.7 Driving Applications

WHITEMECH will ground its scientific results in real **application domains** to demonstrate the effective usability of the scientific achievements of the project. Specifically the project will develop **tools for white-box self programming in Smart Spaces (IoT), Process-Aware Information Systems (BPM) and Smart Manufacturing (Industry 4.0).**

Interestingly, all the applications in these domains involve structuring a set of activities over time and hence can take advantage of Business Process Management (BPM) [87, 86]. However differently form standard BPM applications, both smart spaces and smart manufacturing require integrating

sensing and actuation through a large number of devices/production-islands/robots, which enable the system's elements to sense, react, and collect and exchange data. This give rise to so called **Dynamic BPM systems**, originally studied to handle dynamic contexts such as emergency management [134]. These can indeed be exploited for developing smart spaces (the PI and his group have collaborated with TevereEterno (cf. http://www.tevereterno.it/) to design a public smart space on the Tiber river within the Project ICE: Immersive Cognitive Environment), and smart manufacturing solutions. The latter give rise to the most complex applications, where manufacturing plants use information technology, i.e., databases, sensors, motors/actuators, computerized controls, etc., to manage each specific stage or operation of a manufacturing process. The challenge is to integrate individual stages of manufacturing production enabling data sharing throughout the plant [54].

The interplay of IoT, AI-based techniques, cloud computing, Software-as-a-Service (SaaS), and BPM forms what may be called a "Cognitive Cyber-Physical Systems". Such systems can monitor the physical processes enacted in cyber-physical environments, create a virtual copy of the physical world and make informed decisions, by introducing methods of self-optimization, self-configuration, self-diagnosis, and intelligent support of workers in their increasingly complex work [163]. In such systems, synthesis of component orchestrators, which WHITEMECH can provide, is the main ingredient for allowing the required run-time flexibility. Such processes, whose enactment is influenced by user decision making and coupled with contextual data and new knowledge acquired from the cyber-physical environment, realize the vision of *Cognitive Process Management Systems* (CPMS) [110], and **WhiteMech can be instrumental for their actual realization**.

As an example, in the production process of an Italian ceramic sanitary-ware factory, a system is used to manage and control the workings of the robot lines employed in the various steps of the production process of a sanitary item. Each element of the factory is wired and smart, i.e., attached to sensors and actuators, and has the necessary software to operate as part of the system, which provides continuous monitoring of the (relational) data generated by the robot lines involved in the production process. Furthermore, a typical production process also includes humans whose intelligence and actions are necessary for the given process. It is well known that when a failure occurs in ceramic materials, the result is often catastrophic [116]. But even in the most advanced factories, exceptions and product defects (e.g., deformations) are identified and mitigated only *after* the fact, i.e., after the final step of the production process. Thus there is now a push to install 3D scanners at different steps of the production line. The scanners use structured-light (PLS) technology for capturing digital 3D scans of the sanitary surfaces, generating high-resolution digital 3D models, which can be used to track product deformations during the various stages of the production line. Data detection made by 3D scanning is then be used to develop mathematical models that help to predict deformations of ceramic items. However, whereas today the data collected by 3D scanning are thought to be used to optimize the process *off-line*, a CPMS could act *on-line*, by first detecting if the deformations of the mould model (during one of the steps of the manufacturing process) are different from the ones expected when developing the initial CAD model, and then by changing the manufacturing process to synthesize procedures that mitigate the deformation. For example, a possible process can instruct the maintenance crew which is present on site to remove a prototype of the mould model before the manufacturing process is completed (e.g., if a deformation after the drying stage is evaluated as critical and no longer "adjustable", it is useless to glaze and bake the prototype). A further procedure may command the oven to modify its temperature to fix some deformation caused by the drying step by making the baking step more effective. Exploiting the data generated by the 3D scanners, the system can detect and resolve disturbances at run-time before they escalate and result in product defects. A system that optimizes the whole production process by reducing unexpected costs and maintaining quality, is the concrete outcome of applying synthesis techniques studied in WHITEMECH to the smart manufacturing scenario.

In WHITEMECH we will consider 3 applications, the first one in **Smart Spaces**, where we will build upon the scientific results for finite-state mechanisms; the second one on more traditional **Process-Aware Information Systems**, where we will aslo include data, and the final one on **Smart Manufacturing** that will involve all scientific aspects of the project. The work on these applications will be carried out in collaboration with Tiziana Catarci, Ioannis Chatzigiannakis, Massimo Mecella, and Andrea Vitaletti at Sapienza, whose main expertise is in these application domains. In addition, a

scientific collaboration on Smart Manufacturing will be set up with Brian Logan's research group at U. Nottingham, UK.

The PI and his group have significantly contributed to these application domains, see e.g., [61, 62, 84]. Moreover the PI has already applied with success advanced science to real application domains in the past, specifically, in the area of Semantic Data Integration where he and his group have invented the Ontology-Based Data Access paradigm, possibly the most successful approach for Semantic Data Integration [143, 164, 115]. Such an approach has matured to the point that the PI founded a Sapienza start-up **OBDA Systems** (http://www.obdasystems.com) to commercially exploit Ontology-Based Data Access in real data integration scenarios.

a.8 High Risk, High Gain

WHITEMECH is a **high risk, high gain project**. It is **high gain** since, if successful, it will result in radically more useful automated mechanisms unleashing the full potential of self-programmability and removing the main barriers to an extensive use of automated mechanisms in real applications, namely the restriction to predefined forms of automation which is high-cost and error-prone, and the difficulty of formally analyzing their automated behavior in human-comprehensible terms. Given the crucial role that automated mechanisms play in our modern economy and society and that white-box self-programming mechanisms have the potential to resolve a number of central hurdles, this implies a potentially very high impact on Computer Science as well as in crucial business contexts, facilitating the already ongoing uptake of automated mechanisms in industry, and eventually also on economy and society at large. As a result, WHITEMECH is **very timely** and of **greatest significance for European Science**.

WHITEMECH involves **high risk** because ultimately we need to merge explicit representations, with advanced forms of process synthesis/coordination and refinement, and identify novel and useful classes of effective feasibility. What WHITEMECH aims at is technically extremely challenging, touching upon several notorious open problems in Planning, Reasoning about Action, and Synthesis. On top of that, the path from theoretical analysis to practically efficient algorithms, which we plan to fully explore within WHITEMECH, is a huge challenge given that WHITEMECH aims at realizing real automated mechanisms to be deployed in real business applications. Despite the challenges that WHITEMECH will face, the general **feasibility** of WHITEMECH is demonstrated by the PI original, exploratory publications [82, 79, 80, 60, 77, 64] and follow-ups [173, 50]. The track record of the PI guarantees that the **project will result in far-reaching results** that are exciting for all of the four scientific communities involved, as well as for the driving application domains.

Risk management. The main risk is that synthesizing mechanisms for declaratively expressed goals (e.g., in LTL_f or LDL_f) by reducing to Classical, FOND or POND Planning will result in planning domains that are "puzzle-like" and do not scale well, even after optimizations such as those in [18, 17, 161]. We consider this risk unlikely, since the original problem is not "puzzle-like" and in compiling the formula the crucial structure is maintained [82, 79, 80]. In any case, this can be mitigated by considering relevant fragments of $\text{LTL}_f/\text{LDL}_f$, cf. [5, 29], or those used in declarative business process models [175, 60, 74].

A second major risk is that lifting from propositional to first-order states may give rise to unmanageable models. Indeed it is known that even for bounded-state data-aware processes, the worst-case complexity is exponential in the relational data that are allowed to change during process execution. While possible, this risk is mitigated by the availability of a well-developed theory, with algorithms and tools, for (unfaithful vs. faithful) abstraction [58, 16, 16, 119], on the bases of which one can under/over approximate the model for the synthesis task. Such approximations have already been used for model checking in the context of data-aware processes in [104, 20].

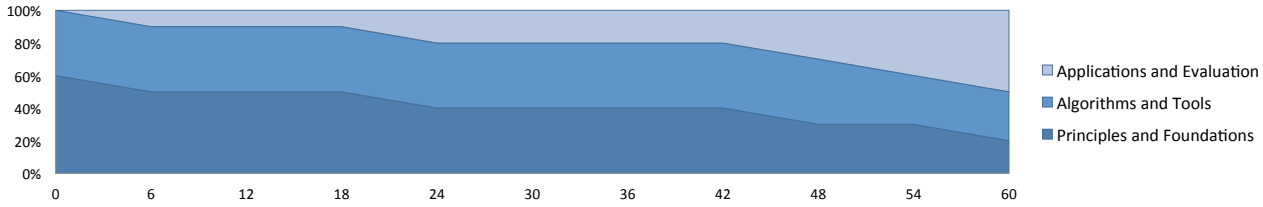
Overall the PI is exceptionally well-positioned to face the challenges that WHITEMECH *will present.*

b Methodology

The scientific work in WHITEMECH will be methodologically structured into 3 broad research streams:

– **Principles and Foundations**, which will deal with the scientific foundations of white-box self-programming mechanisms.
– **Algorithms and Tools**, which will deal with the development of practical algorithms, optimizations and tools for realizing such mechanisms.
– **Applications and Evaluation**, which will evaluate white-box self programming mechanisms in the three business critical applications mentioned above.

The percentage of work in the 3 streams over the course of the project is reported in the figure below.



The **Principles and Foundations** and **Algorithms and Tools** streams will cut across 6 work-packages (WPs) roughly corresponding to the 5 project objectives (cf. B1). The **Applications and Evaluation** stream will be carried out in a specific WP further refined into the 3 driving application domains. The WPs are detailed in the following.

WP1: Querying and Synthesis in Finite-State Models (m0–m36)
Aim: Develop the core theory, algorithms and tools for white-box self-programming mechanisms in a finite-state setting *(cf. Objective 1 and 2)*. The WP produces the key milestone M1 at month 18. After the milestone, the WP continues with refinements until month 36.
Milestone: (M1) first iteration of documents and associated software for theory, algorithms and tools for Querying and Synthesis in Finite-State Models (m18).
Team: *Sapienza personel:* Fabio Patrizi, Andrea Marrella, Luca Iocchi and Camil Demetrescu (cf. Resources); *to be hired:* 2 Senior PostDocs one on Planning and one Synthesis, 1 Junior PostDoc (on 2+3 contract) on software development (maintaining this role also when the WP finishes), 1 PhD student; *external collaborators:* Hector Geffner (UPF, Barcelona), Blai Bonet (U. Simon Bolivar, Caracas), on Planning; Moshe Vardi (Rice U., USA) Sasha Rubin (U. Napoli, Italy), and Benjamin Aminof (TU Wien, Austria) on Synthesis; Nello Murano (U. Napoli, Italy) on parallel algorithms for Multicore/GPUs [10, 11].

WP2: Querying and Synthesis in Component-Based Models (m6–m36)
Aim: Extend the core theory, algorithms and tools for componentization of white-box self-programming mechanisms in a finite state setting *(cf. Objective 4)*. The WP produces the key milestone M2 at month 24. After the milestone, the WP continues with refinements until month 36.
Milestone: (M2) first iteration of documents and associated software for theory, algorithms and tools for Querying and Synthesis in Component-Based Models (m24).
Team: *Sapienza personel:* Fabio Patrizi, Andrea Marrella, Massimo Mecella; *to be hired:* 2 Senior PostDocs working on Planning and Synthesis respectively (shared with WP1), 1 Junior PostDoc working software development (shared with WP1), 1 PhD student; *external collaborators:* Sebastian Sardina (RMIT, Melbourne, Australia), and Alfonso Gerevini (U. Brescia, Italy).

WP3: Querying and Synthesis in Relational-State Models (m18–m54)
Aim: Lift the WHITEMECH techniques from the finite state case to a first-order setting which is able to deal with relational data *(cf. Objective 3)*. The WP produces the key milestone M3 at month 36. After the milestone, the WP continues with refinements until month 54.
Milestone: (M3) first iteration of documents and associated software for theory, algorithms and tools for Querying and Synthesis in Relational-State Models (m36).
Team: *Sapienza personel:* Maurizio Lenzerini, Riccardo Rosati, Domenico Lembo, Antonella Poggi and Marco Ruzzi; *to be hired:* 1 Senior PostDoc, 1 Junior PostDoc, 1 PhD student; *external collaborators:* Yves Lesperance (York U., Toronto, Canada), Hector Levesque (U. Toronto, Canada), Yongmei Liu (Sun Yat-sen U., Guangzhou, China) on reasoning about action, and Rick Hull (IBM Research, USA), Jianwen Su (UCSB, USA) and Alessio Lomuscio (Imperial College, London, UK) on data-aware processes.

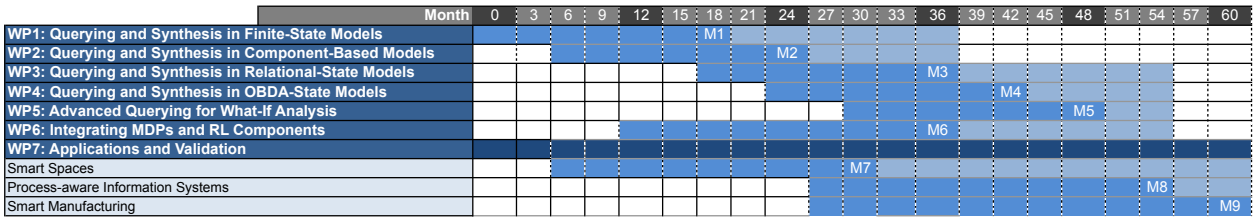
WP4: Querying and Synthesis in OBDA-State Models (m24–m54)
Aim: Move the WHITEMECH techniques from flat relational states to a setting with semantically rich state descriptions *(cf. Objective 2,3)*. The WP produces the key milestone M4 at month 42. After the milestone, the WP continues with refinements until month 54.
Milestone: (M4) first iteration of documents and associated software for theory, algorithms and tools for Querying and Synthesis in OBDA-State Models (m42).
Team: *Sapienza personel:* Maurizio Lenzerini, Riccardo Rosati, Domenico Lembo, Antonella Poggi, Domenico Fabio Savo, and Valerio Saltarelli; *to be hired:* 1 Senior PostDoc (shared with WP3), 1 Junior PostDoc (shared with WP3), 1 PhD student; *external collaborators:* Diego Calvanese and Marco Montali (U. Bolzano, Italy), and Ernest Teniente (U. Politecnica de Catalunya, Spain).

WP5: Advanced Querying for What-If Analysis (m30–m54)
Aim: Develop advanced forms of query answering over white-box self-programming mechanisms that enables What-If Analysis *(cf. Objective 2)*. The WP produces the key milestone M5 at month 48. After the milestone, the WP continues with refinements until month 54.
Milestone: (M5) first iteration of documents and associated software for theory, algorithms and tools for Advanced Querying for What-If Analysis (m48).
Team: *Sapienza personel:* Maurizio Lenzerini, Riccardo Rosati, Domenico Lembo, Fabio Patrizi, Andrea Marrella, Tiziana Catarci, Giuseppe Santucci; *to be hired:* 1 Junior PostDoc, 1 PhD student; *external collaborators:* Daniele Magazzeni (King's College, London, UK) on Explainable Planning; Sasha Rubin (U. Napoli, Italy) and Benjamin Aminof (TU Wien, Austria) on counterfactuals in synthesis.

WP6: Integrating MDPs and RL Components (m12–m54)
Aim: Extend WHITEMECH techniques to handle also MDPs and RL Components *(cf. Objective 5)*. The WP produces the key milestone M6 at month 36. After the milestone, the WP continues with refinements until month 54.
Milestone: (M6) first iteration of documents and associated software for theory, algorithms and tools for Integrating MDPs and RL Component (m36).
Team: *Sapienza personel:* Fabio Patrizi, Luca Iocchi, Andrea Marrella; *to be hired:* 1 Senior PostDoc, 1 PhD student; *external collaborators:* Ronen Brafman (Ben-Gurion U. Israel), Hector Geffner (UPF, Barcelona, Spain), Blai Bonet (U. Simon Bolivar, Caracas).

WP7: Applications and Validation
Aim: Apply and validate WHITEMECH technology in 3 driving application domains, namely: *Smart Spaces* (IoT), *Process-aware Information Systems* (BPM), *Smart Manufacturing* (Industry 4.0).
Milestones: (M7) release of demonstrator in the context of Smart Spaces of finite-state mechanisms: it evaluates results of WP1 and WP2 (m30); (M8) release of demonstrator in the context of Process-aware Information Systems of relational-state and OBDA-state mechanisms: it evaluates results of WP3 and WP4 (m54); (M9) release of demonstrator in the context of Smart Manufacturing of full-fledged mechanisms: it evaluates results of WP5 and WP6 and the whole project (m60).
Team: *to be hired:* Tiziana Catarci, Ioannis Chatzigiannakis, Massimo Mecella, and Andrea Vitaletti; *to be hired:* 2 Junior PostDocs (on 2+3 contract), 2 PhD students. *External collaborators:* Brian Logan and Natasha Alechina (U. Nottingham, UK) on composition in smart manufacturing.

The WP timings are reported in the figure below.



All results of the project, including software, will be made publicly available. Moreover we will organize workshops on the themes of the project at major conferences such as ECAI, or IJCAI when in Europe, to disseminate and communicate the results of the project and to engage in community building.

c Resources

The PI, Giuseppe De Giacomo, will dedicate 70% of full time involvement to the project at a cost of €326.200. In addition, the following Academic/Research Staff in the Department will dedicate a smaller proportion of their time to the project, at a total cost of €291.600: Full professors: Tiziana Catarci (HCI, h-index=35), Maurizio Lenzerini (KR&DB, h-index=74), Riccardo Rosati (KR&DB, h-index=50); Associate professors: Ioannis Chatzigiannakis (IoT&I4, h-index=31), Camil Demetrescu (Parellel algorithms, h-index=26), Luca Iocchi (Planning, h-index=37), Domenico Lembo (KR, h-index=32), Massimo Mecella (BPM, h-index=30), Giuseppe Santucci (DB, h-index=25); Assistant professors (ricercatori): Fabio Patrizi (Planning, h-index=18), Antonella Poggi (KR&DB, h-index=23), Andrea Vitaletti (IoT&I4, h-index=21). PostDocs: Andrea Marrella, Marco Ruzzi, Domenico Fabio Savo, and Valerio Saltarelli. In addition, the project will hire 4 Senior PostDocs for 3 years each (*Ricercatore a Tempo Determinato di tipo A* which cost €45.887 per year of which 75% on the project), 6 Junior PostDocs, 3 of which are on 2+3 year contracts and 3 on 2 year contracts, (*Assegno di Ricerca*, €30.600 per year of which 90% on the project), and a total of 8 PhD students (PhD), each on a 3 year program (€16.433 per year of which 70% on the project). External collaborators will be at no cost, except for visits (see below).

The **total cost** of the project is €2.499.197. The **direct costs** cover personnel cost for €1.719.357, including the cost of researchers already staffed, and the new hires described above. Overhead amounts to 25% of direct costs. **Equipment costs** of €11.000 cover the acquisition of a Multicore/GPU rack to experiment with parallelization of the planning/synthesis process. **Travel costs** amount to €153.000 (approx. 12 trips per year at €2.500), and include both the cost for participation to international conferences and workshops, and dissemination and communication events for the personnel, as well as the cost for visiting external collaborators listed in the project. The project does not have any subcontracting cost. However, as stated above, the project will benefit from the numerous collaborations that our team has with external groups and €90.000 (approx. 6 visits per year at €3.000) are allocated for the visit of external collaborators to our Department. €12.000 are allocated for publication expenses; this amount is limited because some of the top journals in AI have a free open access policy, e.g. JAIR, and AIJ (open access through the IJCAI site). Finally, the cost of €14.000 for the audit certificate is also included.

c.1 Budget

Cost Category			**Total in Euro**
Direct Costs	**Personnel**	PI	326.200
		Senior Staff	291.600
		Postdocs	826.083
		Students	276.074
		Other	0
	i. Total Direct Costs for Personnel (in Euro)		1.719.357
	Travel		153.000
	Equipment		11.000
	Other goods and services	Consumables	0
		Publications (including Open Access fees), etc.	12.000
		Visits by external collaborators	90.000
		Audit certificate	14.000
	ii. Total Other Direct Costs (in Euro)		280.000
A - Total Direct Costs (i + ii) (in Euro)			1.999.357
B - Indirect Costs (overheads) 25% of Direct Costs (in Euro)			499.839
C1 - Subcontracting Costs (no overheads) (in Euro)			0
C2 - Other Direct Costs with no overheads (in Euro)			0
Total Estimated Eligible Costs (A + B + C) (in Euro)			2.499.197
Total Requested Grant (in Euro)			2.499.197

Please indicate the duration of project in months:	60
Please indicate the % of working time the PI dedicates to the project over the period of the grant:	70%

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