Semantic City Planning Systems (SCPS): A Literature Review

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Semantic City Planning Systems (SCPS): A Literature Review

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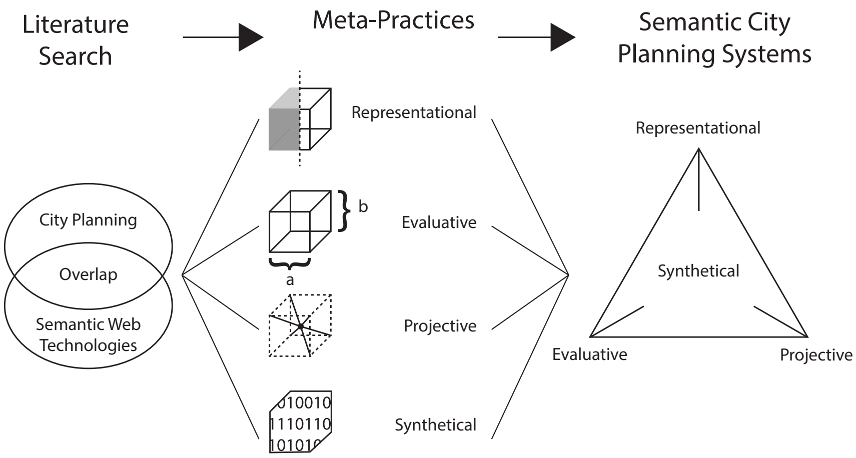
Abstract

This review focuses on recent research literature on the use of Semantic Web Technologies (SWT) in city planning. The review foregrounds representational, evaluative, projective, and synthetical meta-practices as constituent practices of city planning. We structure our review around these four meta-practices that we consider fundamental to those processes. We find that significant research exists in all four meta-practices. Linking across domains by combining various methods of semantic knowledge generation, processing, and management is necessary to bridge gaps between these meta-practices and will enable future Semantic City Planning Systems.



Highlights

- We collect literature at the intersection of City Planning and Semantic Web Technologies (SWT).
- We structure this body of research along representational, evaluative, projective, and synthetical meta-practices fundamental to City Planning.
- We find that significant research exists to develop Semantic City Planning Systems (SCPS).

Contents

1 Introduction **3**

2 Background **5**

2.1 Semantic Web Technologies (SWT) 5

2.2 Methods for Design Synthesis 7

2.3 Digital Urban Planning 8

3 Methodology **9**

3.1 Defining and Scoping SCPS 9

3.2 Building a Collection of SCPS Literature 10

4 Reviewing the state of the art of SCPS **11**

4.1 Representational MP 12

4.2 Evaluative MP 13

4.3 Projective MP 15

4.4 Synthetical MP 16

5 Conclusions **19**

References **22**

1 Introduction

Rapid urbanisation has seen cities grow in size and number at unprecedented speed worldwide [157]. Beginning in nineteenth-century Europe, evolving in twentieth-century Americas and accelerating exponentially in the early decades of the twenty-first century in Asia and Africa, urbanisation has produced a sharp rise in consumption of energy, land and metals and other raw materials. This, in turn, has increased green-house gas emissions that contribute to climate change [148]. Planning and managing the growth of cities today and in the near future is widely regarded as essential if we are to address the challenge of climate change and the host of associated issues – such as mitigating pollution, food security, and social equity – that underpin long-term liveability and sustainability [141].

Mainstream city planning emerged in nineteenth-century England, continental Europe and the United States alongside urbanisation and industrialisation. It took shape as a rational and public-spirited response to new societal challenges triggered by those processes such as managing pollution, sanitation and public health, providing affordable housing for growing populations, integrating new utilities like gas and electricity, and delivering efficient urban transportation [69, 2]. Planning developed hand-in-hand with new social scientific, statistical and cartographic techniques needed to empirically record the various social, economic and physical aspects of rapidly growing cities [66, 68, 140].

Planning has historically been associated with a top-down reduction in complexity, resulting in a particular plan that is considered a 'solution' satisfying a set of requirements to an agreeable extent *e.g.* a master plan). However, reductionist conceptions of planning often ignore the inherent complexity and interconnected nature of urban systems, in which problems are 'wicked' [130] and the system 'unknowable' [106, 198-201], and 'unsolvable' without acknowledging the complexity of the system [14, 33]. As a result, at present time, planning often emphasises the process of dialogue and consensus building, rather than the product.

The discipline also diversified in response to changing political and social mores in the twentieth century. This saw an increasing multisectoral outlook, with greater involvement of private sector interests and civil society through participatory planning movements. At the same time, a growing interdisciplinarity in planning was accompanied by a tendency towards fragmentation into various sub-disciplinary socioeconomic, environmental and physical design-oriented traditions [60, 68, 121].

The increased pace of urbanisation today and its implication in climate change places new demands on city planning. These demands, which focus directly on the empirical traditions of the discipline, concern improving the credibility, timeliness and diversity of evidence to support the planning of sustainable cities. Harnessing the rise of information communication technology (ICT), big data and artificial intelligence (AI) has been regarded as imperative to meet these demands [154, 156]).

City Planning (CP) has been integrating the growing availability of digital data. The rise of Geographic Information Systems (GIS) and, more recently, agent-based modelling in land-use studies (*e.g.* 'Agent-based modelling of city systems' Systems 2016), and various digital planning support tools e-governance and entrepreneurial governance systems have become central the discipline [11, 26, 145]. Despite these recent advances, Batty [12], Helbing and Pournaras [70] note that CP has yet to effectively harness the full possibilities of the ICT revolution. The exponential growth in quantity of data on cities and city processes, has been supported by improved capacities to store and manage those data and make them available to city-making stakeholders across the board. And yet, mainstream CP efforts still generally rely on two-dimensional planning maps for land-use zoning, simple ratios to indicate maximum densities, and rigid metrics for environmental performance. Even if these kinds of data are digitised and made available on websites, they remain relatively static, without standardised exchange formats and difficult to cross-reference and analyse [95]. The many new digital tools that have emerged lack, as Dominic Stead puts it, a 'framework for categorizing, analyzing, and comparing' them [145]. Providing such a framework would rely on developing 'a better system of validation and critical assimilation of scientific knowledge' into city planning [107, 267].

There are many possible reasons for the relative hesitancy of city planning to harness digital data. They may concern the way the discipline itself has tended to prioritise the craft of planning rather than tending to its scientific foundations [107]. They may also concern the interdisciplinary and multisectoral character of the discipline which tends to generate distinctive sub-disciplinary specialisations in the face of rising interdependency of social, economic and physical dimensions of cities. They may also concern the data themselves. Although more numerous, big data are typically sourced in many different formats, are stored in distinctive siloes, and managed in inconsistent ways. Big data, in other words, are often unstructured, not linked and provide hurdles to being integrated.

This review focuses on the last of these possible reasons. It does so by focusing on recent developments in the field of Semantic Web Technology (SWT). SWT is an area of innovation in the digital revolution that offers a promising approach to solving the difficulties with data fragmentation and supporting the more effective use of big data in planning. SWT is promising in this context because it focuses on structuring and linking data, making it more searchable and accessible. In the context of CP, it has the capacity to improve the interoperability of data across different sectors, disciplines and knowledge domains.

For the purposes of this review, we define CP in section 3.1 as a complex task that requires four Meta-Practices (MP) that occur simultaneously during CP processes: *Representational MP*, *Evaluative MP*, *Projective MP*, and *Synthetical MP*. Our purpose is to better support planning practice, and its ability to address the challenges of urbanisation, demographic shift and climate change with Semantic City Planning Systems (SCPS) at the intersection of CP and SWT – see Fig. 1.

In section 2 we provide a short overview of digital urban planning and describe how SWT present opportunities for CP and how planning-related knowledge is represented in this context. We explain and define SCPS as a necessary endeavour for future CP in section 3. We define the scope of this literature review in section 3.1. Section 3.2 describes how we built the body of literature of this review. We take a particular interest in planning support tools or systems and the digital artefacts used to support them. We arrange the found literature and uncover research gaps that we present in section 4. We structure our findings along four MP with section 4.1 on Representational MP, section 4.2 on Evaluative MP, section 4.3 on Projective MP, and section 4.4 on Synthetical MP. We discuss and unify the found research niches under SCPS in section 5.

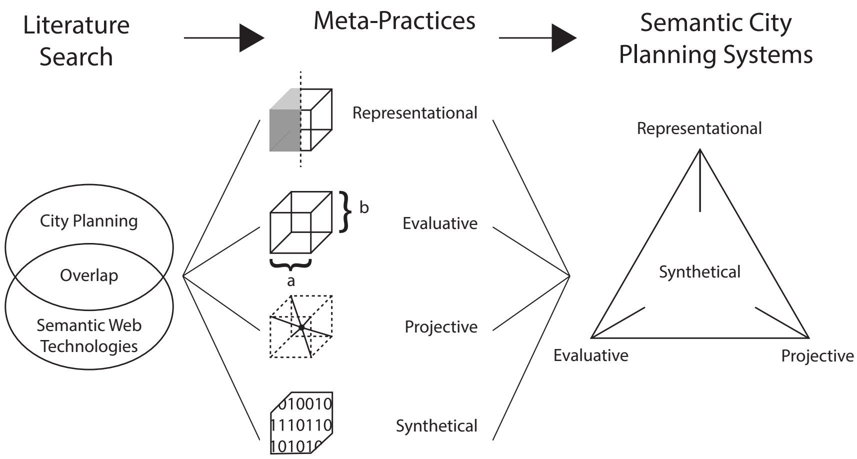


Figure 1: *The literature found at the intersection of City Planning (CP) and Semantic Web Technology (SWT) is structured along four meta-practices forming Semantic City Planning Systems (SCPS).*

2 Background

This background section situates three main domains that form the foundation of SCPS: SWT in subsection 2.1 and their potential for CP, concepts of knowledge representation of planning and design processes in subsection 2.2, and an overview of the diverse state of the art of digital urban planning in subsection 2.3. These three background subsections help to locate similar research based in SWT in section 4.

2.1 Semantic Web Technologies (SWT)

SWT are built on the concepts of linked data and semantic web. Linked data is data that is structured and interlinked with other data. The semantic web aims to make data on the web machine-readable and interpretable [2, 23]. Semantics relate to the study of meaning, reference, or 'truth' [1], and can be formulated mathematically based in descriptive logic. The semantic web builds on the availability, accessibility of, and the *relationship among*, data [2]. SWT are already transforming the Architectural, Engineering, and Construction (AEC) industries [124]. SWT enable the representation of complex systems forming ever larger connected webs. SWT can facilitate to represent everything of interest or subsets thereof (*i.e.* the world and subsets thereof, such as cities). Machine-readability, scalability, and indifference to the subject of representation promise to overcome current challenges in digitalising CP, namely: the problem of interoperability of data and thus machine readability, the problem of scalability in the face of large and complex systems such as contemporary cities, and the possibility to represent any desirable aspect of cities.

The following terms are crucial in understanding SWT and their potential for CP:

- *Knowledge Representation and Semantics*

By virtue of representing data and the relationship among them, based in descriptive logic, SWT enable more integrated knowledge representation. Semantics can be used to infer information from linked data and allow to set axioms or principles that define knowledge in specific domains.

- *Applied Ontology / Knowledge Domains*

  An ontology represents a common vocabulary that is necessary for data and relationships among them to be understandable, meaningful and replicable. Vocabularies may differ from one knowledge domain to another in detail and complexity. In addition to a consensus vocabulary of concepts, an ontology is also a consensus categorisation and a consensus hierarchy of concepts. Ontology development may use abstraction and invoke other (sub-)ontologies to describe specific knowledge domains. Web Ontology Language (OWL) is commonly used as knowledge representation language (schema) of the semantic web. Once a knowledge domain is identified, one can design, define, and compose ontologies for many different applications and purposes.

- *(Semantic) Triples / RDF / Graph Databases*

  Information in the semantic web is stored in triples of 'subject, predicate, object' to describe the data and the relationship among them. Each triple can thus link to others, forming a web. Resource Description Framework (RDF) is the data modeling framework for the Semantic Web. For semantic CP, it is thus crucial to represent urban data (geo-location, 3D geometry, textures, attributes, dynamic data, *etc.*) as RDF files. SPARQL is a query language for semantic webs designed to query data across systems and data-bases.

- *Knowledge Graph*

  If data is represented as a node, and the semantic relation, guided by the common vocabulary or ontology, as their edge, then semantic webs can be represented as mathematical graphs of semantic triples. Knowledge Graphs (KG) represents the full integration of data and web structure of a semantic system. Inference as the process of reasoning over data through rules allows to extract, fuse, recombine, and represent knowledge. KG have a wide range of applications grounded in the capacity to infer new or previously inaccessible knowledge. For CP this promises to overcome the fundamental challenges associated with current digital planning of 'siloed' expertise; fragmented, incomplete and inaccessible data; ill definition and large scale of problems [122]. KG can for example enable a multi-scalar and multi-domain simulation [47, 123] and the instantiation of Parallel Worlds (PW) scenarios [48].

- *Dynamic Knowledge Graph / agent systems in KG*

  Dynamic Knowledge Graphs (DKG) are systems that can reconfigure the graph structure dynamically, in response to changing context, to new queries, or to their own increased knowledge, by way of multi agent systems embedded into the KG structure. Examples include industrial process engineering and chemistry processes represented with Artificial Intelligence (AI) composition agents to reconfigure the KG as needed [52, 173].

2.2 Methods for Design Synthesis

Marshall [106, 192] argues to recognise "the positive benefits of a complex system of planning, capable of generating functional urban complexity". CP is inherently interdisciplinary with implications on design [108]. The adage that planning deals with the basic question ‘How much of what goes where, and why?’ [72, 25] illustrates that the decisions guided by planning relate to the allocation of resources in urban space. CP necessarily works towards multiple objectives, establishing satisfactory syntheses that integrate information from multiple knowledge domains. Urban designers and planners have developed a wide range of strategies to design and manage urban projects. However, the traded formats of conventional design delivery, namely images, plans, calculations, and models, arguably lack standardised formats to evaluate them. In this subsection we will list some attempts to explicate design processes and to link them to computational methods.

- *Design Heuristics*

  In practice, designing and planning are routed in heuristic approaches and tacit knowledge formation that designers and planners acquire in their education and by experience. These increase the domain knowledge and expand the solution space for a design problem [103]. Designers move from abstract idea elaboration and opportunity-seeking *’design freedom’* to gradually more concrete solutions and reduction through decision-making *’design solutions’* [103]. Such knowledge based in human creativity is hard to systematise and replicate with computers. Hence, the aim of so-called ’computational design’ is to enhance the work of designer with digital methods and tools.

- *Urban Elements*

  First attempts to synthesise urban phenomena in ‘pattern languages’ and to collect them in thesaurus-like manner were made by Alexander [5], Alexander et al. [6]. Alexander’s concept to draw urban information from observation and to infer ‘rules’, ‘elements’, or ‘actions’ for urban knowledge has been revisited by Cairns and Tunas [27], Lehnerer [97], von Richthofen et al. [161]. Quickly, any system of elements requires a meta-system, structure or milieu to be embedded in. Thesauri, such as ‘rules’, ‘elements’, or ‘actions’, can share similar aims and structures as ontologies do in SWT.

- *Design and Shape Grammars*

  Shape grammars developed by Stiny and Gips [146] consists of shape rules and generation mechanisms to create complex forms. Shape grammars can we used to explicate design processes. Shape grammars lead to the development of powerful 3D digital modelling tools. These tools based in procedural form generation [113]. These tools can assist in the automatic and procedural generation of large urban models based in urban development guidelines and zoning codes [160].

- *Design Space Exploration (DSE)*

  Design Space Exploration (DSE) is a concept deriving from futurology aiming to describe potential future event spaces and scenarios resulting from decisions in the past [71, 162]. Similarly, planning can be seen as a temporal process of causal relationships in which data and information is gradually combined to form a *better picture* for decision making: CP unfolds in stages, creating, exploring, and evaluating possible design options, so called design spaces. DSE has been formalised by Fuchkina et al. [56], Pimentel [125].

2.3 Digital Urban Planning

Digital urban planning forms a subset of CP and refers to modelling urban systems and urban forms, developing GIS, planning support systems, and spatial decision support systems, as well as City Information Modelling (CIM) tools.

- *Urban Modelling*

  A first dynamic digital urban model for systems analysis as a tool for urban planning has been developed by Forrester [55]. Forrester suggested to look at urban systems as dynamic interplay of economic, spatial, and social aspects and to model these mathematically for urban simulations. Michael Batty and others built upon the work of Forrester to develop urban analysis models [10, 13].

- *Geographic Information Systems (GIS)*

  GIS allow to represent 3D geographic information digitally [153]. While a range of geo-processing methods are available to analyse and synthesise information, the data-format is limited in its capacity to store and link data.

- *Modelling urban form*

  3D digital modelling of urban forms is concerned with the generation of large and detailed urban geometries. Modelling urban form is based in the study of urban typologies (*i.e.* of buildings, street patterns, densities, *etc.*) and the observation that smaller forms are nested in larger forms following certain structures (buildings group to form blocks, neighborhoods, and precincts, *etc.*). Research focuses on the assembly of rules of typologies and structure to arrive at generative design of urban forms [15, 86]. The rule-based approach to urban modelling has been fast forwarded by Machine Learning (ML) techniques [34, 142, 163]. As König et al. [85] noted, the combinatorial possibilities of automated form generation quickly outpace the possibilities of computers.

- *Planning and Decision Support Systems*

  Planning and decision support systems are a collection of spatial analytical and simulation tools that allow to display (live) geo-spatial and temporal data about cities. These systems often have a ‘dashboard’ visual interface similar to a military ‘situation room’ allowing decision makers and stakeholders to visualise, discuss and decide [58, 67, 145].

- *Digital Urban Twins*

Digital twins complement planning and decision support systems with a virtual 'twin' or model to be used for the analytical and simulation work. Digital twins often incorporate large 3D urban models and link these to other city data bases such as cadastral information and census data [134]. Examples of digital twins include Centre for Digital Built Britain and University of Cambridge [32], CIVAL [39], and the digital twin for the city of Zürich [138].

- *City Information Modelling (CIM)*

  City modelling has been focusing on modelling form and texture for city models that cater to visual applications ranging from navigation, to computer games, cinema, and virtual urban models. City Information Modelling (CIM) emphasises the information aspect and aims to include other data sources such as cadastral information, socio-economic, climatic, environmental, traffic and other data into comprehensive urban models [59]. Challenges to CIM include the problems of lacking data-interoperability and hindered machine processing. For this, CIM are gradually including SWT to overcome these problems [147].

3 Methodology

In this paper, we argue that SWT is particularly suited to support the synthetic, multi-domain goals and tasks of CP. However, as the concept of planning is broad and diverse, the corpus of literature representing the intersection of semantic web and planning literature is fragmented. In order to develop a clearer picture of relevant literature, the present section introduces and uses the term SCPS to indicate possible interfaces between planning and SWT. From this definition, we develop a framework for SCPS to help define the scope of a search through literature, in order to build up a collection of relevant literature.

3.1 Defining and Scoping SCPS

We define SCPS as 'possible uses of SWT to support the process of CP practice'. The practice of planning happens at many different scales, resulting in many related terms, such as regional planning, spatial planning, urban planning, town planning, master planning, infrastructure planning, or urban design, amongst others. Planning is also performed for particular subsets of domains, often systems, *e.g.* transportation planning or sanitation planning, and in professional categories, *e.g.* architecture, landscape architecture, civil engineering, or urbanism. In essence, every one of these disciplines represents a planning process related to cities. We argue that despite the immense variety of activities involved in planning practice, all are essentially anchored in meta-practices – representational, evaluative, projective – in addition to knowledge management as synthetical meta-practice. Knowledge management was previously implicitly incorporated into the representational, evaluative and projective meta-practices. As it is now being enhanced by ICT, big data, and AI a new area of synthetical meta-practice is necessary – and analogous to the SWT approach. As we defined SCPS as the use of SWT *to support* CP processes, we developed a framework of four meta-practices (MP). These MP are common to all planning processes and are meant to facilitate navigating the conceptual space of planning and our scoping of and search for literature and not as mechanical planning devices. They are inherently interconnected and occur simultaneously and not in a particular order.

- **Representational MP** is the act of representing urban systems (*i.e.* urban environments and their parts and processes). These representations are most often visual in nature. Representational MP can be of an entire urban systems or parts of it, representing the totality of that system (*e.g.* 'digital twins') or a selection of its properties (*e.g.* 3D models, maps, evaluation results, . . .).
- **Evaluative MP** is the act of evaluating properties of an urban environment, determining whether they satisfy particular requirements or accomplish goals. Evaluative MP can assess various aspects of urban systems, such as single states (*e.g.* calculating the permeability of street networks), continuous property changes (*e.g.* measuring temperature over time), processes (*e.g.* simulating carbon emissions), or multiple criteria (*e.g.* a SWOT analysis of a site and its properties).
- **Projective MP** is the act of creating specifications of new urban systems or their parts, based on an envisioned or desired (future) urban system or its properties. Projective MP can be performed at many scales (*e.g.* regional plans, master plans, urban design proposals, transport plans), and are often proposed adaptations of existing urban systems.
- **Synthetical MP** is the act of managing, gathering, using, creating, and synthesising data, information, and knowledge about the urban systems that are planned. Though perhaps not often explicitly mentioned, planning processes inherently rely on flows of information, involving actions such as gathering site information, requesting data from various instances or specialists, retrieving past proposals or decisions, documenting processes and methods, building data repositories, or communicating with stakeholders.

3.2 Building a Collection of SCPS Literature

This literature review looks into the body of literature that is the intersection between literature on SWT and literature on CP. However, it was not feasible to develop a standardised or systematic approach to search for and analyse the body of literature at this intersection, for two main reasons. Firstly, as discussed in detail in section 3.1, both SWT and CP are umbrella terms that cover a broad range of concepts and applications. Secondly, both SWT and CP feature words and terms that are ubiquitously used, making it difficult to delineate a corpus of literature through conjunctive keyword queries. Words related to 'city' or 'urban' are very common; the same is true for terms related to 'planning', and the conjunction of related terms. In case of SWT, particular key terms are also used in other fields, such as 'semantic', 'ontology', or terms related to 'knowledge', without referring to SWT in particular. Considering these limitations, our collection of SCPS literature is not intended to be exhaustive. However, the selected body of work allows us to review the topic, provide an overview existing results, discuss different sub-topics and the weight of their coverage, and identify research gaps.

We searched for relevant literature in multiple repositories, using several approaches, the combination of which resulted in a collection of SCPS literature, which we discuss below. The collection for this literature review was built drawing on:

- The authors' pre-existing collection of literature (being researchers studying SCPS).
- Various conjunctive keyword queries in Scopus and Google Scholar, exploring the intersections of particular topics (each 'topic' represented by a set of related terms):
  - 'City Planning' AND 'Semantic Web Technology'
  - 'Planning' AND 'Semantic Web Technology'
  - 'City' AND 'Semantic Web Technology'
  - Each of four 'Meta-Practices' AND 'Semantic Web Technology'
- Keyword searches for terms related to SWT in CumInCAD (a repository of key conferences and journals related to computer aided architectural design).
- Papers suggested by Google Scholar and ResearchGate's recommendation engines.
- Manual crawling of bibliographies and citation chains from particularly relevant papers.

While searching the literature, all sources about 'the use of SWT to support the process of CP' (*i.e.* SCPS) were manually selected for our review collection. Collection items were manually labelled with each of the four MP featuring in the item.

Some of the topics included in our scope and selection do not explicitly mention SWT and CP, nevertheless demonstrate the potential use of SWT to support CP processes. For example, we included key papers about the use of SWT in AEC industry, as it is strongly related to planning, and deals with similar or analogous tasks and problems. In other cases, only a subset of a topic's literature relates to SWT. For example, a large part of the body of research on city information modelling format CityGML does not directly relate to SWT, despite its core structure being inherently semantic and ontological [62] and its next version [91] demonstrating a much closer connection to core SWT practices (see also section 4.1). Also included are sources about planning supported by proto-technologies predating SWT as a field. Even though literature in the field of planning is often related to multiple and interrelated aspects we chose the strongest contributing argument to classify the literature in a respective section. In this article, literature thus appears only in one MP.

4 Reviewing the state of the art of SCPS

We structure our review of the state of the art of SCPS per MP and collect the literature in four sections and tables. Each section starts by introducing relevant application domains and the contributions to SCPS identified in the literature. The tables in each section are organised by domain, contribution to SCPS, and source.

4.1 Representational MP

The following section covers the Representational MP, presented in Table 1. We identified 'foundations' and 'applications' of SCPS Representations:

- Foundations (Table 1, part 1) include BIM-GIS integration to improve interoperability and enable cross-domain representation from one sphere (*e.g.* AEC) to another (*e.g.* cities and geoinformation). The integration and linking of dynamic data aims to capture temporal and periodic data coming from Internet of Things (IoT) data or big data. The visualisation of non-spatial data – such as concensus data or metadata – is of growing interest. Semantic enrichment is concerned with adding meaning to data in a new context and domain of application (for instance BIM data in a GIS environment) and to allow for semantic querying. The foundations also include representation standards based in 202 [3].
- Applications (Table 1, part 2) relate to the development of city models with various functionalities, for instance various Level of Detail (LoD), additional city information, and dashboard compilation of 'vital signs' to assist CP and management. The idea of a 'world avatar' is arguably the widest concept to represent 'everything' of interest to an urban model based on SWT.

The literature grouped in this section covers fundamental aspects of representation. Owing to the spatial and temporal character of urban data, literature in this section covers aspects of geo-spatial representation based in GIS, building systems representation based in BIM, and urban representation based in CIM. These three representational spheres come with standards and protocols of representation that emerged from the specific application range. A large number of papers address the inter-linkage between these spheres. We find that technical aspects related to semantic representation are being addressed for specific domains of AEC and across industries (energy, transport, urban form, *etc.*), but that the linkage of several domains is still lacking. Within the Representational MP, modelling standards need to be developed further to fully integrate and operate across various scales and industries (*e.g.* from BIM to CIM to GIS) towards a better semantic representation of cities. CityGML, as the most advanced standard for city data (geospatial and other), and defined semantically, appears to be strongly suited to integrate SWT into a 'Cities Knowledge Graph'. The representation of semantic data in real time and in a 3D virtual environment is possible. Visualisation of various LoD can be achieved that demand further ontological description, *e.g.* when spaces are found within buildings and these spaces contain further objects, *etc.*

Table 1: *Literature for the Representational MP.*

Domain	**Contribution to SCPS**	**References**
Foundations of SCPS Representation		
BIM-GIS Data Integration and Representation	Improve data interoperability and conversion, enable cross domain representation	Biljecki et al. [20], Donkers et al. [46], Hor et al. [74], Konde et al. [88], Tauscher et al. [150], Wang et al. [165]

Continuation of Table 1		
Domain	**Contribution to SCPS**	**References**
Representing Dynamic Data	Integration of domain data, linking data, graph transformation, data population	Chaturvedi and Kolbe [35], Rowland et al. [132], Tempelmeier et al. [152], Yao and Kolbe [169]
Representation Standards	Modelling standards and specifications for representation in CityGML and CityJSON	Kumar et al. [90], Kutzner et al. [91], Stadler et al. [144]
Semantic Enrichment for Representation	Semantic enrichment of models, create domain ontologies, spatio-semantic coherence, semantic integration, semantic queries	Billen [21], Lim et al. [99], Schwab et al. [139], Wang et al. [166], Yao et al. [168]
Applications of SCPS Representation		
City Dashboards	Dashboard overview, Dashboards for creation, evaluation and data visualisation	Chen et al. [38], Santos et al. [136]
City Models	City model representation, informing domain ontologies, spatial ontologies, support LODs, applications, standards, visualisation	Billen et al. [22], Bonduel et al. [25], Chaturvedi et al. [36, 37], Julin et al. [77], Li et al. [98]
Digital Twins	Support urban development and land management use cases, design optimisation	Boje et al. [24], Montenegro et al. [115]
World Avatars	Build a 'World Avatar' environment	Eibeck et al. [48], Sabag Muñoz and Gladek [135]
End of Table 1		

4.2 Evaluative MP

The literature for the Evaluative MP is organised in Table 2. We group the literature in this section according to the various states of evaluation: single or multi-criteria; monitoring; and modelling.

- Single or multi-criteria evaluation assesses to what extent one or more characteristics of an urban system have reached a certain target. Spatial decision support and design support systems typically require more than one criterion to be assessed. Multi-criteria evaluation is also applicable to other complex assessment and reasoning tasks as well as to the development of ontologies.

- Monitoring refers to reporting and evaluating data-streams (solar irradiation on building surfaces, for instance). Monitoring allows to link various data streams, for instance social media data and big data, and feeds into platforms for urban analytics and semantic data integration for CIM.

- Modelling and Simulation refer to assessing time frames within which states change (for instance the status of an urban lot that changes from 'vacant' to 'construction' to 'built up'). Modelling tackles dynamic data integration as way to represent the multiple and temporal data-streams. Modelling for urban micro-climatic analysis as well as systems modelling are cited use cases.

Dynamic and complex systems such as cities and their subsystems constantly change states. The states and rates of exchange need to be evaluated, monitored and modelled to allow for control and feedback. Single or multi-criteria evaluation allows to determine particular states at given times. Monitoring involves a temporal dimension that allows to observe and evaluate changes in states. This can involve sequential single or multi-criteria evaluations or parallel observations in different locations. Evaluation modelling aims to replicate the interplay of particular states, their change in time and space, as well as their interrelations. The Evaluative MP shows that literature exists to support and inform CP tasks. This section links to the Representational MP – as results of an evaluation can be used to augment representation.

Table 2: *Literature for the Evaluative MP.*

Domain	**Contribution to SCPS**	**References**
Single or multi-criteria evaluation		
Decision support	Spatial decision support, design support systems, form-based assessment, qualitative comparative analysis	Lee et al. [96], Miltiades and Angelides [112], Verweij and Trell [159]
Semantic assessment	Semantic environmental assessment, verification, formalisation and evaluation	Kamsu-Foguem et al. [79], Lai and Zoppi [93], Massaro et al. [109], Trento [155]
Sustainability assessment	Graph-based ontology reasoning, environmental assessment of urban energy usage, reduction in CO_2	Kamsu-Foguem et al. [79], Kardinal Jusuf et al. [81], Konys [89], Lai and Zoppi [93], Lombardini [102], Madrazo et al. [104]
Monitoring		
Dynamic data evaluation	Analysis of social media content, semantic enrichment of big data	Gao et al. [57], Pittaras et al. [126]
Evaluation platforms	Platform for urban analytics and semantic data integration for 3D city models	Psyllidis et al. [129], Yao et al. [170]
Modelling and Simulation		

Continuation of Table 2		
Domain	**Contribution to SCPS**	**References**
Process data evaluation	Temporal data, spatio semenantic modelling, for 3D city models	Kaňuk et al. [83], Schwab et al. [139]
End of Table 2		

4.3 Projective MP

The literature for the Projective MP contains the least number of references – and we identify a clear lack of literature here. We attribute this to the fact that creation in design and planning processes is still under-researched and ambiguous [42]. To overcome this problem, systems of design or design frameworks have been developed [41]. Design Space Exploration (DSE) stands out as a strategy for automated exploration, evaluation, and optimisation of design solutions. Automated creation includes generative computational urban design and planning approaches. The linkage between shape grammars for urban form generation and ontologies promises to automate urban form generation. These examples can be translated, in parts, to machine processes, including advances in replicating complex cognitive tasks such as creativity. The literature organised in Table 3 thus refers to generative processes of creating data, information and knowledge related to planning. In terms of CP, substantial efforts are put on the creation of the physical world, linking in geographic information, 3D geometry, attributes, *etc.* This MP also includes papers focusing on buildings rather than cities. We include these as the research findings are transferable. The table is not further subdivided as other tables for lack of literature found.

Table 3: *Literature for the Projective MP.*

Domain	**Contribution to SCPS**	**References**
DSE frameworks	Systematic and automated design space frameworks including temporalities and complexities	Engel [49], Lin [100]
Generative design systems	Generative computational urban design and planning	Montenegro and Duarte [114], Montenegro et al. [116]
Scenario design	Ontology-based platform for cross-domain scenarios in process industry	Eibeck et al. [47]
Semantic design systems	Ontologies and shape grammars towards semantic design systems	de Klerk and Beirao [44], Grobler et al. [63]
Semantic evaluation and creation tools	Semantic analysis and creation	Armeni et al. [8], Caneparo et al. [30], Gomes et al. [61]

Continuation of Table 3		
Domain	**Contribution to SCPS**	**References**
Semantic enrichment	Semantic enrichment of 3D city models, ontology alignment in the urban domain	Bonduel et al. [25], Calabretto et al. [28], Mai et al. [105], Wagner et al. [164], Wiegand [167]
End of Table 3		

4.4 Synthetical MP

The literature is organised in Table 4. This section contains the most references found at the intersection of SWT and CP. The synthetical MP that involves knowledge management enables data interoperability because all data is represented in ontologies that represent the semantic meaning of the data, rather than just their values. It further enables computational interpretation and synthesis, because all data is has semantic meaning that is machine readable. It promises to open up advanced planning support options, such as parallel simulation of multiple scenarios, automated generation of visualisations and analyses, knowledge inference, and iterative learning.

The Synthetical MP provides a clear foundation for SCPS: linked data allows to perform context-based and network proximity analysis; data structuring forms the base for self-organisation of knowledge bases; fundamental challenges of data interopreability can seemingly be resolved. The management of large and complex 3D urban data appears possible with the application of semantics to spatial concepts, urban modelling, communication, decision support, and knowledge generation. Further knowledge domains can be linked in via ontology development techniques and frameworks. We structure this section into Linked Data and Data Processing; Development of Domain Ontologies; Searches and Information Queries; and Processes, Systems, and Agents.

- Linked Data addresses the core challenge of interoperability from a knowledge management perspective. It covers context-based data detection, dynamic data, spatial granularity, and management.
- Semantic Knowledge Management covers semantic strategies for enrichment and spatial data integration.
- Development of Domain Ontologies follows similar topics with a focus of ontology creation and applications arising from it. These include knowledge generation, semantic design and decision support, semantic urban models and semantic urban planning.
- Searches and Information Queries relate to data structuring, as well as semantic querying and answering as methods to infer knowledge based on the descriptive logic of SWT.
- Processes, Systems, and Agents gathers literature around dynamic systems, agent compositions and systems architecture. Together, they support Dynamic Knowledge Graphs (DKG) for cross-domain scenarios – or Parallel Worlds (PW).

Table 4: *Literature for the Synthetical MP.*

Domain	Contribution to SCPS	References
Linked Data		
Context-based data	Context-based ontologies for urban data, semantic change detection, linked data vocabularies	Hoare et al. [73], McGlinn et al. [110], Med and Křemen [111, 111], Pittaras et al. [126]
Data structuring	Data structuring, development of knowledge bases, self-organisation	Chen et al. [38], Lin [101], Zhang et al. [171]
Dynamic data	Spatial granularity, dynamism, representation of data	Chaturvedi et al. [36], Espinoza-Arias et al. [50], Fonseca et al. [54], van Dam and Keirstead [158], Zhang et al. [171]
Semantic extension of data	Interoperability, extension, integration and linkage of data	Métral et al. [118], Psyllidis [128]
Spatial semantic data	Spatial semantic planning databases, ontology-driven GIS, access methods and dynamic database extension	Karalis et al. [80], Yao and Kolbe [169]
Semantic Knowledge Management		
Management of semantic data	Management, analysis, and visualisation platforms for semantic 3D city data and models	Komninos et al. [87], Psyllidis et al. [129], Yao et al. [170]
Semantic decision support	Semantic spatial decision support system, urban information frameworks, planning informatics	Plume [127]
Semantic enrichment	Semantic alignment, enrichment, integration and verification of data	Iwaniak et al. [76], Tardy et al. [149]
Semantic feedback and communication	Feedback and communication for knowledge management for planning support systems	Murgante and Garramone [119], Ruikar et al. [133]
Semantic knowledge generation	Knowledge generation and retrieval, knowledge graphs, knowledge formalisation and representation	Bereta et al. [17], Karalis et al. [80]

Continuation of Table 4		
Domain	**Contribution to SCPS**	**References**
Semantic spatial modeling	Representation of urban space using semantic urban modelling	Berta et al. [18], Billen [21]
Semantic support applications	Semantic support for Smart City and IoT applications	Baracho et al. [9], Guo et al. [64], Katsumi and Fox [82], Komninos et al. [87], Métral et al. [117], Zhao and Wang [172]
Semantic urban models	Knowledge management and ontology development for semantic urban models	Berdier and Roussey [16], Biljecki et al. [19], Caneparo et al. [29], Guyot et al. [65], Teller et al. [151]
Semantic urban planning	Semantic urban planning, land use and land cover management, planning ontologies, allocation-related master-planning actions	Ahlqvist et al. [4], Gomes et al. [61], Kaczmarek et al. [78], Montenegro and Duarte [114], Ronzhin et al. [131], Soon [143]
Development of Domain Ontologies		
Domain ontology development techniques	Semantic data integration for urban analytics, coupling ontologies and urban design guidelines, capture spatio-temporal phenomena	Cao and Hall [31], Corry et al. [40], Huang and Harrie [75], Psyllidis [128]
Domain ontology development based on dynamic data	Ontology-based GIS and big data analysis	Chaidron et al. [33], Fischer et al. [53], Gao et al. [57]
Searches and Information Queries		
Data city indicators and frameworks	Uniting ontology-based geodata and geovisual analytics	Ding et al. [45], Santos et al. [136]
Knowledge access and discovery	Knowledge access and discovery systems, spatial knowledge retrieval	Lacasta et al. [92], Langenhan [94], Mai et al. [105]
Semantic querying and answering	Spatio-semantic query, answering geo-analytical questions	Daum et al. [43], Scheider et al. [137]
Processes, Systems, and Agents		
Agent composition frameworks	Agent composition frameworks for automated knowledge retrieval	Zhou et al. [173]
Dynamic Knowledge Graph (DKG)	DKG for cross-domain scenarios development, PW built on ontologies and linked data	Eibeck et al. [47]

Continuation of Table 4		
Domain	**Contribution to SCPS**	**References**
Knowledge management and planning support in ontologies	Knowledge management and planning support tools for urban typologies, genres, patterns, and urban design heuristics	Gao et al. [57], Montenegro and Duarte [114], Murgante and Scorza [120], Teller et al. [151]
Smart City representation in ontologies	Smart City representation based in ontologies	Aloufi and Alawfi [7], Komninos et al. [87], Psyllidis [128], Psyllidis et al. [129]
System architecture design of ontologies	Ontological design of system architecture	Falquet et al. [51], Kaza and Hopkins [84]
End of Table 4		

5 Conclusions

In this paper we offer a rationale for planners to take note of SWT and their promising applications to help address some of the fundamental challenges of the practice of CP. We point towards the empirical traditions of CP and the growing interest in data and evidence to support planning decisions. We argue that CP is predisposed to be adopt some form of SWT – as it becomes ever more aware of the growing interdependencies of cities – resulting from the greater scale, accelerated pace, and complexity of cities – that is currently met with disciplinary fragmentation. We present four meta-practices, Representational MP, Evaluative MP, Projective MP, Synthetical MP, expanding the disciplinary triad of representation, evaluation, and projection with the data-synthetic meta-practice emerging to address of the rise of ICT, big data, and AI in relation to planning. We identify emergent traits in the Synthetical MP literature, for it is the largest and most recent body of research. In contrast, the three others build up on disciplinary traits of design and planning. The tetrahedral model of meta-practices introduced in this paper (see Fig. 1) will allow to develop future SPCS.

The literature review points to gaps that will need to be bridged in order for such systems to work. We identify a research gap related to approaches for blending spatial and non-spatial information – and enhancing future CIM with non-visual data. We foresee future research on representation of meaning and knowledge when thinking – for instance – of consensus as a precondition for decision making. We can also imagine the necessity to represent and visualise 'live models' or PW. Similarly, the Evaluative MP needs to be applied to monitoring urban change in order to transform urban data into meaningful long-term indicators (*e.g.* the idea of 'heartbeats of the city'). As scales and complexities increase, ontological frameworks will become necessary to link up the evaluation systems to support multi-criteria decision tasks across all scales of CP. The Projective MP still lacks fundamental ontologies for design, planning, and envisioning tasks. The example of DSE is not meant to be an automated 'design mechanism' but a support strategy. Alternatives to DSE exist and can be explored and translated into ontologies. Similarly to the other MP, the challenge is to link up currently segmented semantic creation methods and to develop more robust generative design systems across all scales of CP. Designers and planners also require intuitive and flexible tools while DKG should enable smooth interaction between users and the system in order to learn and improve itself using AI. Linking across domains could be achieved by combining various methods of semantic knowledge generation, processing, and management. The Synthetical MP suggest that the foundations for a DKG, built on SWT, linked open data and AI, are available.

The presented literature on SCPS – at the intersection of CP and SWT – is thus not meant to be a 'mechanical' recipe for planning, but a guide to bring closer two groups of readers (researchers and practitioners) to the field of SCPS: geographers, city planners and urban studies scholars on one side – and data scientists, software developers and programmers on the other. We believe that the sketched synthesis between CP and SWT is going to be a new frontier for planning in the near future. Our vision is to further enhance digital CP and CIM – aiming to develop SCPS with the ability to dynamically infer knowledge in an effort to create the next generation of digital urban twins.

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List of abbreviations

AI	Artificial Intelligence
AEC	Architecture, Engineering, and Construction
BIM	Building Information Modeling
CIM	City Information Modeling
CP	City Planning
DKG	Dynamic Knowledge Graph
DSE	Design Space Exploration
GIS	Geographic Information System
IoT	Internet of Things
KG	Knowledge Graph
LoD	Level of Detail
MP	Meta-Practice
OWL	Web Ontology Language
PW	Parallel Worlds
RDF	Resource Description Framework
SCPS	Semantic City Planning Systems
SWOT	Strength, Weakness, Opportunities, and Threats
SWT	Semantic Web Technologies

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