system, that the heart is an element of that system, and that the heart does not pump blood apart from its belonging to the cardiovascular system.

Functions and purposes are separated by one hierarchical layer in a nested system-of-systems, but purposes at one level are not the same as functions at the next, except by coincidence. So, for instance, that a function of the heart is to pump blood, and that circulation of blood is a purpose of the cardiovascular system, does not entail that pumping blood is a purpose of the heart (i.e., an end served by functions of the heart chambers or cardiac valves), nor does it entail that circulating blood is a function of the cardiovascular system in the human organism, although both hypotheses are, in practice, reliable starting points for iterative analysis.

3 Design in Systems Engineering

3.1 "Design" as a Verb

"Design" as a verb is a rational or economic act of requirements transformation. In systems engineering, requirements are transformed through many stages: from user requirements to system operational requirements through conceptual design, from system operational requirements to element functional requirements through preliminary design, and from element functional requirements to production requirements (specifications, schematics etc.) through detailed design. This process, the concatenation of conceptual design, preliminary design, and detailed design, is shown below in figure 1 (adapted from Blanchard and Fabrycky (1981), MIL-STD-499B (1994), and IEEE Std 1220 (1998)).

The process of engineering design develops efficient applications of resources to satisfy needs. The economic or rational aspect of design, combined with inherent functional allocation in design, distinguishes designs from other arrangements of parts for a collective purpose by a technologically relativistic analogue to Weinberg's criterion of elegance, the economy of means to an end so that nothing is invoked other than what is functionally justified (Weinberg, 1992, 135).

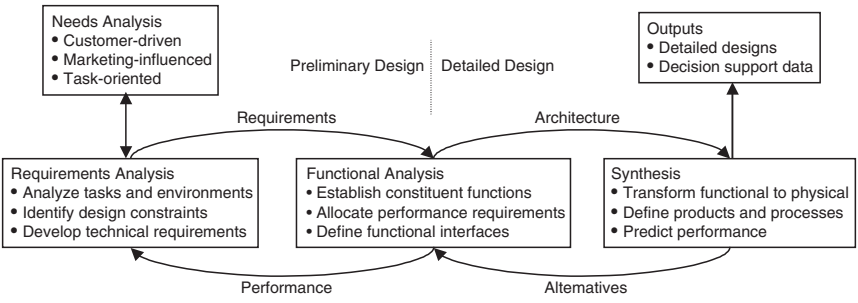

Fig. 1 Design process in systems engineering

The outputs of engineering design are product and production specifications in sufficient detail to eliminate interpretation, variation, or artistic inspiration in the production process. Design results in detailed procedures for processes, detailed algorithms for software, and detailed blueprints for manufacture, without addressing those aspects of production that can be accepted by the engineer as known technique or established art (Aristotelian *technikos*).

Requirements transformation in design is inherently risky: requirements interpreted from one perspective to another cannot be analytically guaranteed to close, e.g., having the elements each meeting their functional requirements in preliminary design does not logically guarantee that the system will meet its operational requirements, etc. This is because requirements transformations are both hierarchical and interpretive: the requirements at each level are expressed in terms natural to the perspective of that level. User needs are expressed in the user's terms with the user's measures of effectiveness, system operational requirements are expressed at the system level, element functional requirements are expressed in discipline-specific functional terms (e.g., electrical, mechanical, control), schematics are expressed in manufacturing and materials terms, etc.

3.2 "Design" as a Noun

In keeping with the definition of designing as an inherently rational or economic activity, "design" as a noun is the rationale, i.e., cognitive analytic basis, for the requirements transformations inherent or implicit in, expressed or embodied in, or imputed to the structural, functional, and process relationships between the system, its environment, and its parts or elements.

"Design" as a noun is not the outcome of "design" as a verb; schematics and specifications are not designs but rather the façades of design, i.e., the interface from design to production, a summary of design sufficient for production. That there is more to a design than is captured in schematics and specifications is evident when designs are protected as proprietary, or delivered from a vendor to a customer in cases of contracting design, or archived for future use. What is included in an archived design, or in a design delivered under a standard contract, or is protected as proprietary when safeguarding designs, includes performance analyses, trade studies, and the development of those alternative system concepts that were evaluated but not, in the end, chosen for production (DAU 2000). In any of these cases what is included in the object called a "design" is the entire rationale for the requirements transformations specified in the design process.

Complementing the distinction between the noun "design" and the products of the activity called "design" is the distinction between comprehending the design of something, e.g., the human heart, and inferring the prior occurrence of an act of design; to acknowledge the design of something is only to judge that the relationships between elements and their capabilities at successive hierarchical levels of nested systems are rational or economical. The rationality of design is an analytical rationality rather than an etiological rationality.