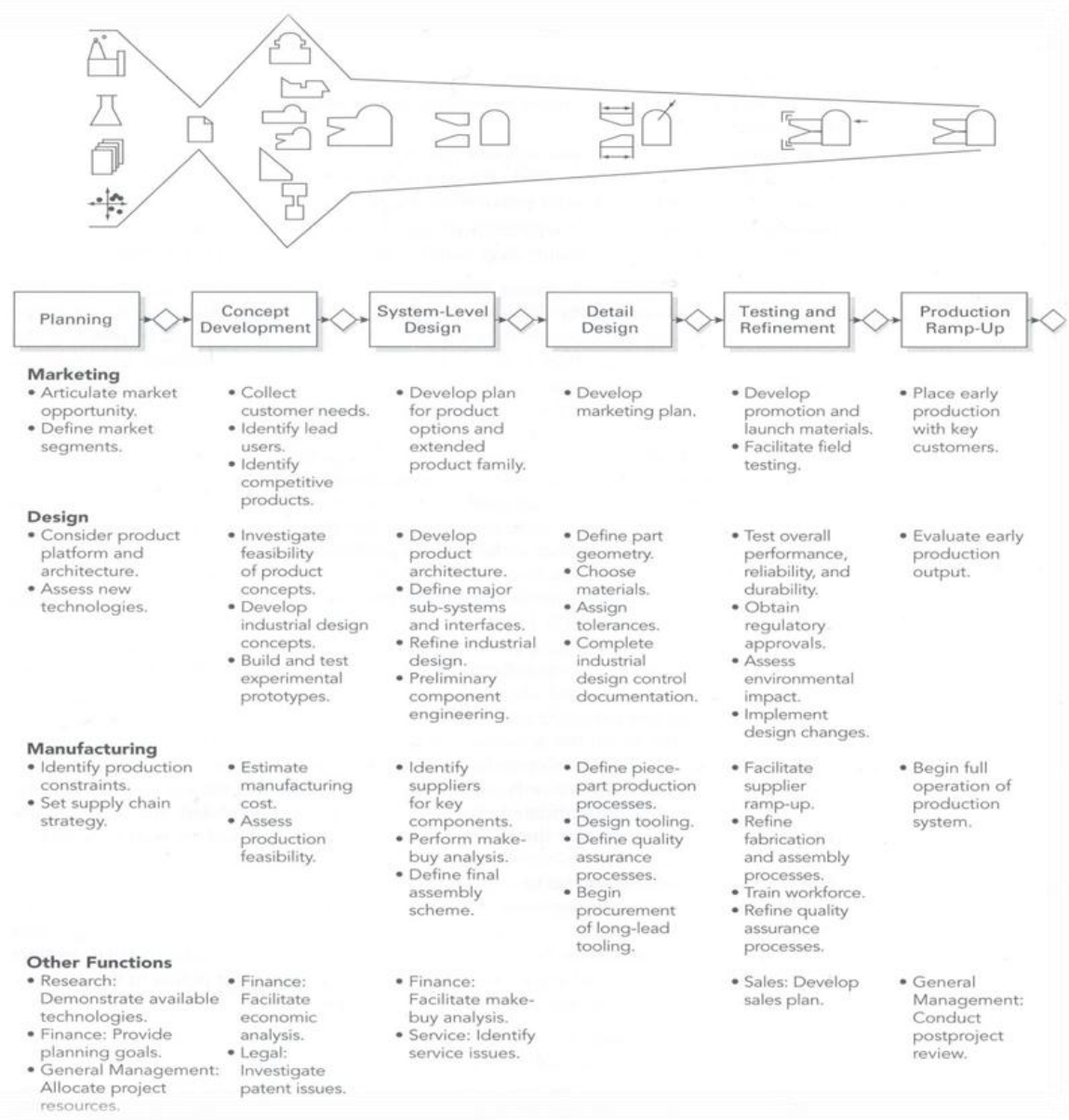
Appendices

Appendix 2.1: The generic NPD process along the typical roles of each phase. (ULRICH & D.EPPINGER, 2012)



Appendix 2.2: Software available in support of Simultanous Engineering information-flow management. (RADHAKRISHNAN et al., 2008)

Design	*Planning/Manufacture*	*Visualization/Simulation*
Solid modeling	Process planning	Factory Simulation
Surface modeling	ERP	Simulation software for-
Assembly modeling	Generative machining Shop floor data collection	• Welding • Casting
Sheet metal design	Human machine interface	• Forming
Drafting	Job tracking	• Forging
Tolerance analysis	Work in process inventory	• Plastic injection molding-
Mechanism design	tracking	• Robot operation
Finite Element analysis	PDM, VPDM and PLMSoftware for-	• Machining etc.
Harness design	• EDM	• Rapid Prototyping
Mold design	• Wire EDM	
Mold flow analysis	• Press brake	
Dynamic analysis	• Grinding	
Thermal analysis	• Turret Punch Press	
Composites design		
Piping design		
Optimization		
Tool design		
Standard part libraries		

Appendix 3.1: Summary of main AM techniques. (MCKINSEY & COMPANY, 2013b)

- **Selective laser sintering (SLS).** In this technique, a layer of powder is deposited on the build platform, and then a laser "draws" a single layer of the object into the powder, fusing the powder together in the right shape. The build platform then moves down and more powder is deposited to draw the next layer. SLS does not require any supporting structure, which makes it capable of producing very complex parts. SLS has been used mostly to create prototypes but recently has become practical for limited-run manufacturing. General Electric, for example, recently bought an SLS engineering company to build parts for its new short-haul commercial jet engine.

- **Direct metal laser sintering (DMLS).** DMLS is similar to selective laser sintering but deposits completely melted metal powder free of binder or fluxing agent, thus building a part with all of the desirable properties of the original metal material. DMLS is used for rapid tooling development, medical implants, and aerospace parts for high-heat applications.

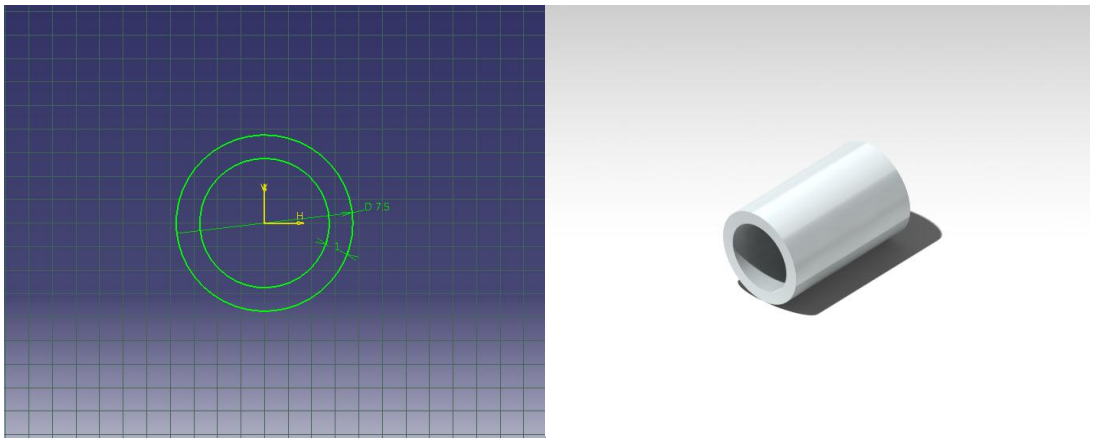
- **Fused deposition modeling (FDM).** A filament of plastic resin, wax, or another material is extruded through a heated nozzle in a process in which each layer of the part is traced on top of the previous layer. If a supporting structure is required, the system uses a second nozzle to build that structure from a material that is later discarded (such as polyvinyl alcohol). FDM is mainly used for single- and multipart prototyping and low-volume manufacturing of parts, including structural components.

- **Stereolithography (SLA).** A laser or other UV light source is aimed onto the surface of a pool of photopolymer (light-sensitive resin). The laser draws a single layer on the liquid surface; the build platform then moves down, and more fluid is released to draw the next layer. SLA is widely used for rapid prototyping and for creating intricate shapes with high-quality finishes, such as jewelry.

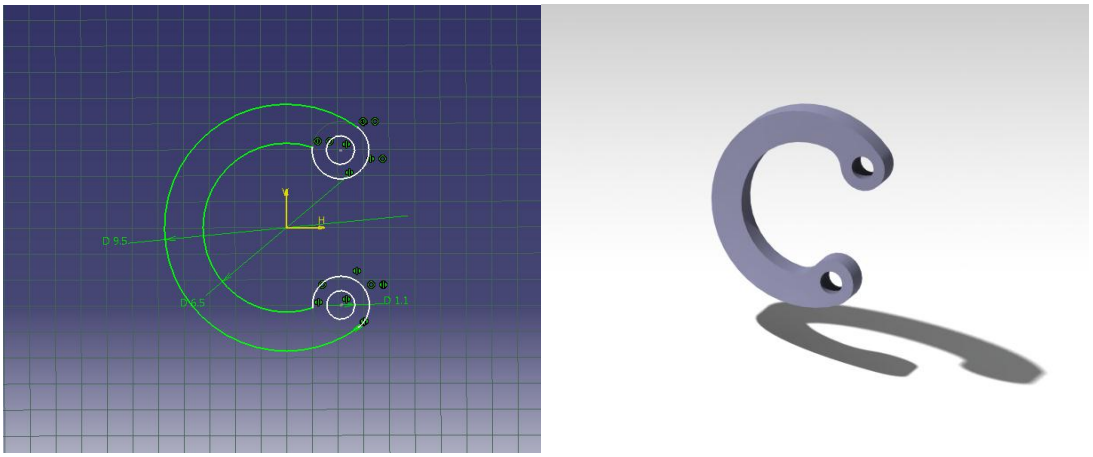
- **Laminated Object Manufacturing (LOM).** A sheet of material (paper, plastic, or metal) is fed over the build platform, adhered to the layer below by a heated roller, and a laser cuts the outline of the part in the current layer. LOM is typically used for form/fit testing, rapid tooling patterns, and producing less detailed parts, potentially in full color.

- **Inkjet-bioprinting.** Bioprinting uses a technique similar to that of inkjet printers, in which a precisely positioned nozzle deposits one tiny dot of ink at a time to form shapes. In the case of bioprinting, the material used is human cells rather than ink. The object is built by spraying a combination of scaffolding material (such as sugar-based hydrogel) and living cells grown from a patient's own tissues. After printing, the tissue is placed in a chamber with the right temperature and oxygen conditions to facilitate cell growth. When the cells have combined, the scaffolding material is removed and the tissue is ready to be transplanted.

Appendix 5.1: Piston pin and piston snap ring design. (Source: own work)

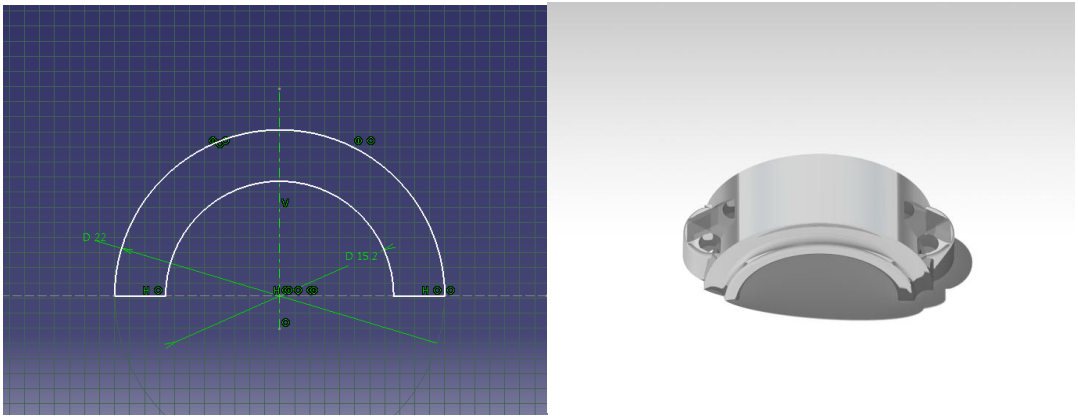


Piston pin sketch design with final render. (Source: own work)

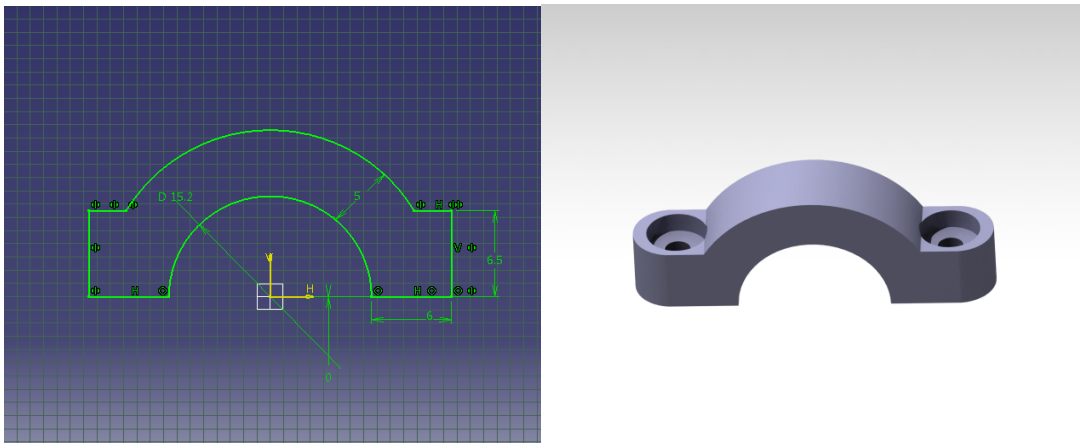


Piston snap rind sketch design with final render. (Source: own work)

Appendix 5.2: Connecting rod cap and crankshaft bearing design. (Source: own work)



Connecting rod cap sketch design with final render. (Source: own work)



Crankshaft bearing sketch design with final render. (Source: own work)

Appendix 7.1: Table of AM material consumption. (Source: own work)

	Values for one part			**Values for n parts**	
	Volume of build material **[ccm]**	Volume of support material **[ccm]**	Part frequency in the model **[n]**	Volume of build material x n **[ccm]**	Volume of support material x n **[ccm]**
AM the model as a single part	463,23	96,56	1	463,23	96,56
AM the cylinder block as designed	299,5	30,48	1	299,5	30,48
AM the crankshaft as designed	57,35	21,19	1	57,35	21,19
Insert liner	16,12	1,2	4	64,48	4,8
Connecting rod	3,71	1,97	4	14,84	7,88
Connecting rod cao	0,98	0,78	4	3,92	3,12
Piston	4,29	2,42	4	17,16	9,68
Piston pin	0,26	0,1	4	1,04	0,4
Crankshaft bearing	1,53	0,71	3	4,59	2,13
Snap ring	0,06	0,15	4	0,24	0,6
Optimized crankshaft	29,96	5,18	2	59,92	10,36
lateral pannel of the block	20,43	2,27	8	163,44	18,16
Middle pannel of the block	25,13	7,43	3	75,39	22,29
Outskirt pannel of the block	28,57	4,72	2	57,14	9,44

Scenario	Volume of build material for scernario **[cm3]**	Volume of support material for scernario **[cm3]**	Material Consumption in total **[cm3]**	material cost (including indirect costs) **[CZK/cm3]**	**Total costs [CZK]**
A	463,23	96,56	559,79	14,4	**8061**
B	463,12	80,28	543,40	14,4	**7825**
C	462,16	88,86	551,02	14,4	**7935**
D	397,68	84,06	481,74	14,4	**6937**
E	254,67	68,17	322,84	14,4	**4649**

Appendix 7.2: Subtractive process incurred costs calculation. (Source: own work)

	Costs per part	**Cost for 4 parts**
Material cost **[CZK]**	24	96
Task average duration **[min.]**	7	28
Machine hour rate [**CZK/h**]	400	400
Direct machine hour costs **[CZK]**	46,67	186,67
In total	**71**	**283**

Appendix 7.3: Subtractive process incurred costs calculation. (Source: own work)

Characteristic	Value
Vessel inner proportions **[mm]**	122 x 67 x 44
Vessel volume **[ccm]**	359,656
Master model volume **[ccm]**	20,430
Silicone mold volume **[ccm]**	339,226
Linear shrinkage **[%]**	<0.1 (neglected)
Silicone specific gravity **[-]**	1,090
Silicone mold mass **[g]**	369,756
Used silicone **[g]**	400,000
Silicone cost **[CZK/g]**	0,34
Silicone mold direct material cost **[CZK]**	137,20
Task measured duration **[min]**	95
Labor rate **[CZK/h]**	100,00
Labor direct cost **[CZK]**	158,33
MOH costs (10% direct material costs) **[CZK]**	13,72
Silicone mold cost **[CZK]**	**309,25**

Appendix 7.4: Incurred costs of casted parts manufacturing. (Source: own work)

Characteristic	Value
Mold cavity volume **[CZK]**	20,43
Resin linear shrinkage **[%]**	0.13 (neglected)
Resin density **[g/ccm]**	1,080
Resin mass **[g]**	22,064
Averagely used resin mass **[g]**	25,000
Resin costs **[CZK/g]**	0,136
Casted part direct material costs **[CZK]**	3,40
Task average duration (including part removal) **[min]**	10
Labor rate **[CZK/h]**	100,00
Labor direct costs **[CZK]**	16,67
MOH costs (10% direct material costs) **[CZK/part]**	0,34
Casted part costs **[CZK]**	**20,41**
Number of casted parts	8
Cost of 8 casted parts **[CZK]**	**163,25**

Appendix 7.5: Processing incurred costs calculation for each scenario. (Source: own work)

Scenario	Additive Manufacturing costs [CZK]	Subtractive process costs [CZK]	Casting process costs [CZK]	Total costs [CZK]
A	8061	0	0	**8061**
B	7825	0	0	**7825**
C	7935	0	0	**7935**
D	6937	283	0	**7220**
E	4649	283	473	**5404**