



DESIGN AND MANUFACTURE CASE STUDY

The Use of Systems Engineering Tools in the
Design Development of a BMX Cassette Hub

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Background

Introduction

Freehubs have become the most widely used type of BMX Freestyle rear hub, as riders have more and more opted for the smaller gearing afforded by the integrated mechanics of these hubs, which, compared to the separate cassette systems, allows for a much smaller drive cog, and are seen as a reliable system. For market driven reasons, pawl-based engagement systems have largely become the standard, due to their low cost and the relatively consumable nature of these parts, which either break or are replaced regularly regardless of how robust they are.

BMX wheels are expected to be able to withstand incredibly rough use, which will all be transferred in some way to the hub. Grind “pegs” are often attached to the axles, which will then be subject to further bending and torsional stresses from peg impacts with hard surfaces, as well as bending stresses transferred through the wheels via the hub. These stresses are mitigated by the additional support afforded by the bicycle frame, to which the hub is mounted, usually by threaded axle, or less often, by bolt-through female axle and slotted dropouts. Often during tricks using the pegs, the hub will also accidentally be subject to direct impacts and abrasions to the side caps and to the body from hard and/or rough surfaces, with the frequency and strength of these accidental impacts dictated by the skill of the rider.

The forces exerted on a rear hub generated solely from pedalling this type of bike are relatively low by comparison to a high end road bike hub or that of a BMX racer, which can see upwards of 100 Nm of force, however on tricks that result in the rider landing backwards and backpedalling, or that otherwise require the locking of the back wheel with pedal pressure, significant levels of torque can be transferred to the engagement mechanism and hub via the driver and chain.

Due to the relatively small market for BMX parts, and the cost of manufacturing specialist components to the standard required, the majority of hub manufacturers rely on certain standard components produced externally for use in their engagement systems. Components such as the pawl spring(s), bearings, pawls, and the internal-ring gear they engage with, are generally off the shelf components produced by specialist manufacturers.

More recently an increasing number of hub manufacturers have started to incorporate various ratchet-based engagement systems in their hub design, both due to the system’s perceived increased robustness and reliability, and as the cost and availability of in-house production for some of the components of these systems has dropped over time to allow a product price-point sufficiently close to that of pawl based systems.



Figure 1: Flybikes "Magneto" Ratchet system hub

Requirements

While cassette hubs are not a new product, their design has been heavily influenced by previous hubs intended for road-bike or mountain bike usage, and due to the relatively small market size for BMX, their manufacture is semi-dependent on use of common components manufactured for other types of hub. Requirements have been derived below for BMX-specific hubs, and the specialised functions these must fulfil.

Functional/Consumer requirements:

Generic Requirements derived are presented below in Table 1:

Number	Originator	Requirements
1	Customer	The hub must be as robust as possible
2	Customer	The hub must engage with the chain to power the back wheel in one direction only
3	Customer	The hub must provide adequate protection for the spokes during grinds
4	Customer	The hub must fix securely to the frame
5	Customer	The axle must be able to withstand multiple impact and torsional loads from peg use and large drops
6	Customer	The engagement mechanism must not slip or jam when pedalling or under high loads
7	Customer	The hub should be stronger than the wheel around it
8	Customer	The engagement mechanism should engage quickly and reliably
9	Customer	The hub should fit 14mm dropouts and can be used with or without pegs
10	manufacturing	Pawl engagement systems should use off-the-shelf or otherwise cheaply produced small components to allow a low product price point
11	Customer	The hub should be relatively lightweight
12	manufacturing	the hub should allow for the use of standard sealed bearing sizes
13	manufacturing	the hub must use a 48 spoke flange and be compatible with standard aftermarket spokes

Table 1: Derived Generic Requirements

The above requirements were rationalised by entering into a pairwise grid and rating the level to which interactions between requirements in each column are complimentary or otherwise in terms of functional effect to each row. This is in order to provide a normalised score for the importance of each requirement. This can be seen in Figure 2 below:

	Pairwise comparison of requirements 1 = No Preference, Reciprocal = 1 2 = Slight Preference, Reciprocal = 0.5 5 = Preference, Reciprocal = 0.2 9 = Strong preference = 0.11	1	2	3	4	5	6	7	8	9	10	11	12	13	Calc	Calc
		The hub must be as robust as possible	The hub must engage with the chain to power the back wheel in one direction only	The hub must provide adequate protection for the spokes during grinds	The hub must fit securely to the frame	The axle must be able to withstand multiple impact and torsional loads from peg use	The engagement mechanism must not slip or jam when pedalling or under high loads	The hub should be stronger than the wheel around it	The engagement mechanism should engage quickly and reliably	The hub should fit 14mm dropouts and can be used with or without pegs	Pawl engagement systems should use off-the-shelf or otherwise cheaply produced	The hub should be relatively lightweight	the hub should allow for the use of standard sealed bearing sizes	the hub must use a 48 spoke flange and be compatible with standard aftermarket spokes	Row Product	nth root of row product
1	The hub must be as robust as possible	1	1	9	9	9	9	9	5	5	0.2	0.11	1	1	32477	2
2	The hub must engage with the chain to power the back wheel in one direction only	1	1	1	9	1	9	1	5	1	0.2	1	1	1	81	1
3	The hub must provide adequate protection for the spokes during grinds	9	1	1	1	1	1	2	1	1	1	1	1	1	18	1
4	The hub must fit securely to the frame	9	1	1	1	9	1	5	1	5	1	1	1	1	2025	2
5	The axle must be able to withstand multiple impact and torsional loads from peg use	9	1	2	9	1	1	9	1	5	1	0.5	1	1	3645	2
6	The engagement mechanism must not slip or jam when pedalling or under high loads	9	5	1	9	9	1	5	9	1	0.2	1	1	1	32805	2
7	The hub should be stronger than the wheel around it	9	1	2	9	9	1	1	1	1	1	0.2	1	1	291.6	1
8	The engagement mechanism should engage quickly and reliably	5	5	1	5	5	9	1	1	1	0.2	1	1	1	1125	2
9	The hub should fit 14mm dropouts and can be used with or without pegs	5	1	5	9	9	1	2	1	1	1	1	1	2	8100	2
10	Pawl engagement systems should use off-the-shelf or otherwise cheaply produced	0.2	0.5	1	1	9	0.2	0.5	0.5	1	1	0.5	1	1	0.023	1
11	The hub should be relatively lightweight	0.11	1	0.5	0.5	0.2	0.2	0.2	0.5	0.5	0.5	1	1	0.5	1E-05	0
12	the hub should allow for the use of standard sealed bearing sizes	1	1	1	1	9	1	1	1	1	1	1	1	1	9	1
13	the hub must use a 48 spoke flange and be compatible with standard aftermarket spokes	2	1	0.5	1	1	1	1	1	1	1	1	1	1	1	1

Figure 2: Pairwise comparison of Requirements

Here, any relationship where the desired behaviour will be enabled by the fulfilment of each requirement or otherwise depends on its successful implementation, are rated either 1, 3 or 9 while a reciprocal preference to the contrary are rated 0.11, 0.2 and 0.5. This enables a simple multiplication formula for each row that will in effect, score the behaviour negatively or positively to the relevant degree and produce a rating. These results were then normalised to enable a comparison. The results of this exercise were charted and the results are presented in Figure 3 below.

As can be seen, the three requirements with the highest importance in terms of their benefits to other requirements and dependencies on others, are for the hub to be robust, for the engagement mechanism to operate reliably, and to allow for a 14mm minimum diameter axle.

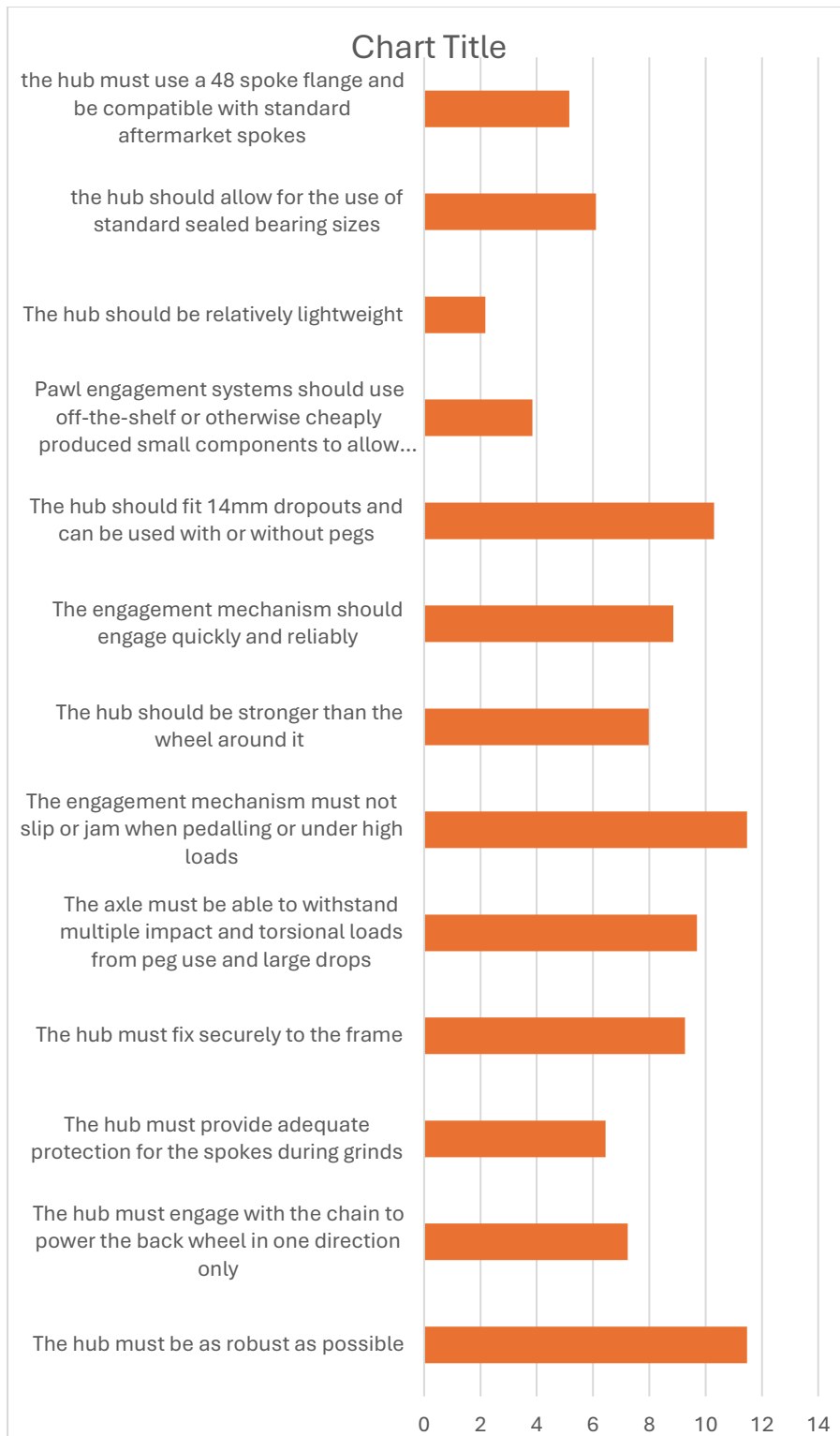


Figure 3: Charted results of Pairwise Comparison

Concept

Architecture

Hub body assembly

Hub body – CNC machined out of aluminium, Comprises flanged largely cylindrical body, with perforations on flanges for spokes, and interface surfaces bearing races and engagement gear

Engagement gear (mechanism for ratchet drive) (hardened steel internal ring gear or star-ratchet, permanently fitted to hub body).

Sealed bearing races – one large Outer diameter (OD), two 14mm internal diameter (ID) races under non-drive flange, and 1 next to the driver as per figure 4.



Figure 4: Cutaway of cassette hub

Driver assembly

Driver body – CNC machined out of Aluminium, comprises the driving cog on one half, with a machined inner surface to seat the axle bearings, with mounting surfaces and recesses for engagement mechanism components, and an O-ring seal with the hub body.

Engagement mechanism - either ratchet star gear or sprung pawls to engage drive teeth on hub body. Pawls usually located in recessed joints machined into driver, and mechanism is either collectively sprung or individually.

Roller bearing race to interface with axle.

Axle Assembly

Axle – hardened steel axle, threaded on both ends with M14 thread, with bearing stops and mounting surfaces for hub body bearings, and mounting surfaces for driver bearing race.

Drive-side lock-nut – Machined nut to hold driver in place on axle, provides some protection to driver bearings and mating surface for frame dropouts

Non-drive-side cone – screws onto axle on non-drive side to protect bearings from damage and provide mating surface for frame dropouts.

Washers and Nuts to fix axle in place in slotted dropouts.

Function Means Analysis

Using the above concept architecture, a list of components applicable to each function was produced as per figure 5 below. It is worth noting that steel pawl pins are optional and will be replaced with locator seats machined into the hub driver and alternative pawls. This should not affect the analysis as it will be considered under separate controls.

Function	Means												
Build Wheel			hub body	driver body									
Install hub	axle nuts	axle-nut washers	axle	driver body									
engagement mechanism functions and powers wheel forwards	axle nuts	axle-nut washers	driver bearing	driver body	pawl springs	pawls	inner-ring gear	hub body	hub body bearings	axle	locking nut	pawl pins	o-ring
hub freewheels	axle nuts	axle-nut washers	hub body	hub body bearings	pawl springs	pawls	inner-ring gear	axle	driver body	pawl pins			o-ring
withstand shocks to axle	axle nuts	axle-nut washers	driver bearing	hub body bearings	hub body	locking nut	locking cone						
withstand impact from hard surfaces	hub body	hub-body bearings	locking nut	locking cone									
wheel rotates backwards and engages mechanism	axle nuts	axle-nut washers	driver bearing	driver body	pawl springs	pawls	inner-ring gear	hub body	hub body bearings	axle	pawl pins	o-ring	
Remove hub	axle nuts	axle-nut washers	axle										
Service wheel	axle nuts	axle-nut washers	driver bearing	hub body bearings	locking nut	locking cone	hub body	axle	driver body	o-ring			
Install/Remove pegs	axle nuts	axle-nut washers	axle										

Figure 5: Component against function

QFD2

Using the list of components and functionality, a QFD2 grid was populated. Each instance was given a rating to represent the level of importance each component holds to each function. This can be seen in figure 6 overleaf.

Unsurprisingly, given it's functions, the axle is highlighted as an importance component here, with the axle nuts and washers second. As is apparent, a secure fixing holding the axle to the frame, and a strong axle is highly beneficial to the effective operation of the hub, as is the effective operation of the hub bearings. Figure 7 shows these results charted for comparison.

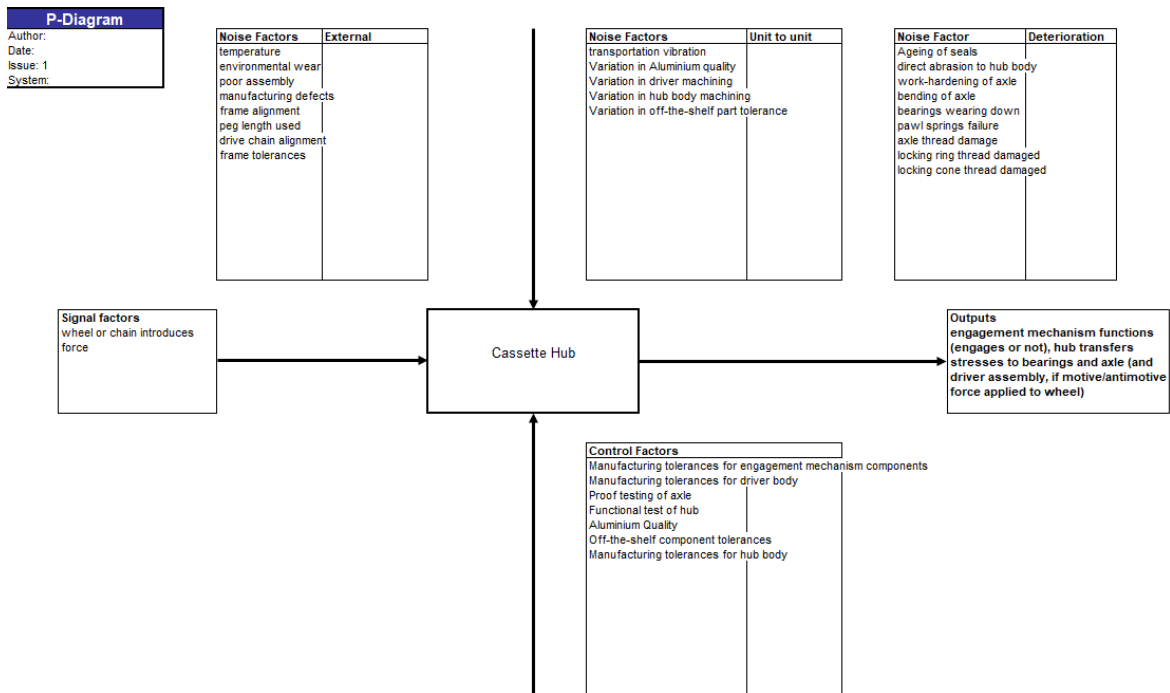


Figure 8: P Diagram of Noise Factors affecting outputs

Performance Characteristics	of design parameter	Weighting	NOISE FACTORS																							Relative Importance of noise in meeting performance via control factor
			Unit to Unit Variation					Deterioration									External									
			Mfg	Mfg	Mfg	Mfg	Mfg	Raw Mat	Raw Mat	Raw Mat	Raw Mat	Raw Mat	Raw Mat	Raw Mat	Raw Mat	Environment	Environment	Human	Environment	Environment	Environment	Environment	Environment	Total		
			transportation vibration	Variation in Aluminium quality	Variation in driver machining	Variation in hub body machining	Variation in off-the-shelf part tolerance	Ageing of seals	direct abrasion to hub body	work-hardening of axle	bending of axle	bearings wearing down	pawl springs failure	axle thread damage	locking ring thread damage	locking cone thread damage	temperature	environmental wear	poor assembly	manufacturing defects	frame alignment	peg length used	drive chain alignment	frame tolerances		
Design control parameters		9	1	9	9	9				9	9	9	1	1			3	3	3		3		63	567		
Manufacturing tolerances for engagement mechanism components	9	1	9	9	9	1				9	9					1		3	3				39	351		
Manufacturing tolerances for driver body	9		9		3		8	9								1		3		8			52	468		
Proof testing of axle	9	8	9	9	9	3						8	3	3			3	9	3				69	621		
Functional test of hub	9		9	9	9		9							8					1				46	414		
Aluminium Quality	9			9	9			3	3	3	9						3						48	432		
Off-the-shelf component tolerances	9		9	9	9	9											3	9					39	351		
Manufacturing tolerances for hub body	9		9		9	9											3	9								
Relative importance of noise factor:			0	261	486	405	432	9	189	108	270	81	162	90	117	27	18	54	189	198	0	81	27	0		
Team:																										
Date completed:																										
		100																								

Figure 9: Noise Factors analysis

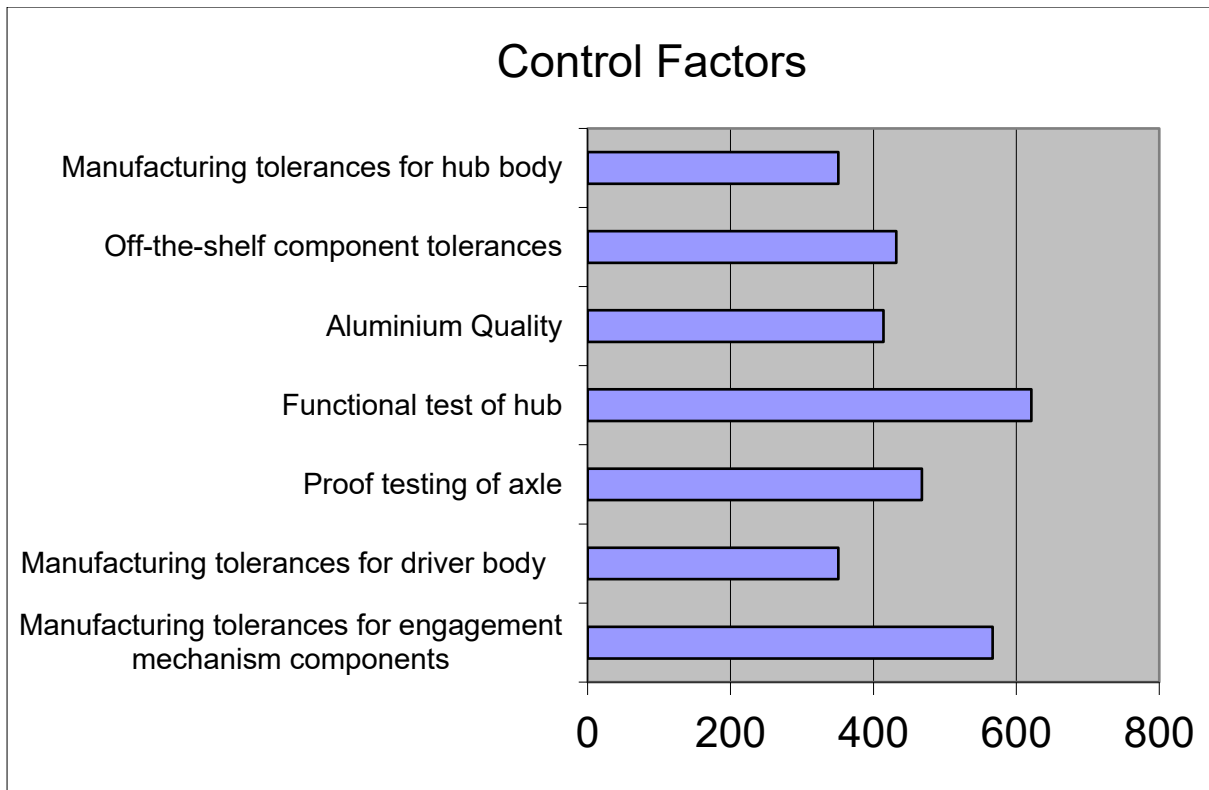


Figure 10: Control Factors Importance

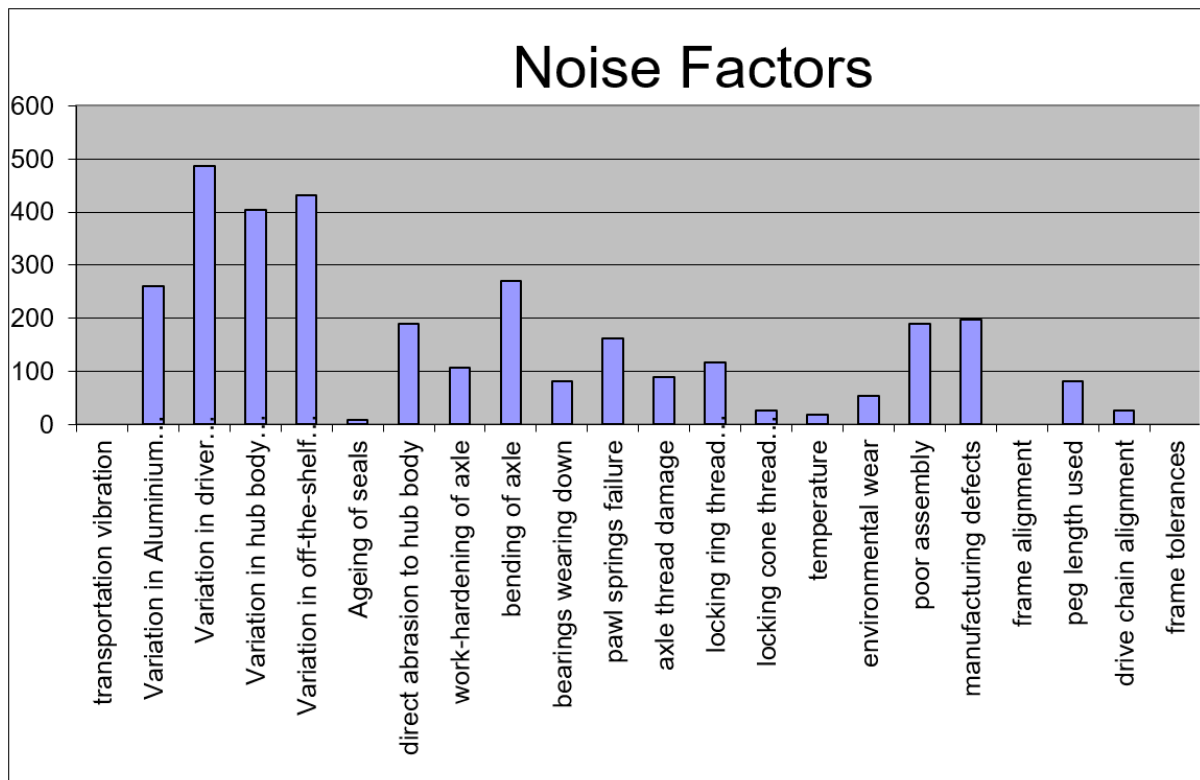


Figure 11: Noise Factors Importance

Component Functionality

The Concept Architecture was broken down into its individual components and listed here in the below table alongside the functions they fill.

Component	Functionality
axle	Provides means of attachment to BMX Frame
	Provides mounting surface for driver bearings
	Provides mounting surface for hub body bearings
	Provides mounting surface for pegs
	transmits shocks from wheel into bmx frame
axle washers	distribute shock and force across axle nut
axle nuts	tighten against frame and axle thread to secure axle to BMX frame
locking nut	tighten against roller bearing inner race and axle thread to hold driver
	Interface with frame to ensure good mating surface
Locking cone	Tighten against hub bearings inner race to provide environmental protection
	Interface with frame to ensure good mating surface
Hub body	Provide mounting holes for wheel spokes
	Provide mounting surfaces for bearings
	holds engagement mechanism in place
	rotates around axle when wheel in motion
Engagement Gear	Provide engagement surface for pawls
	Transmit force between driver and hub body
Hub bearings	rotate around axle while wheel is in motion
	transmits forces from hub body into axle
Driver body	Engages with drive chain
	Rotates around axle when chain in motion
	provides mounting recesses for pawls
	provides mounting surface for bearings
	provides mounting recesses for pawl springs
	provides mounting recesses for pawls
	provides mounting recess for o-ring
	creates seal with hub body
driver roller bearing	Rotates around axle
	transmit forces from driver to axle
Pawl springs	push pawls into engagement gear
pawls	engage with gear on hub body
	transmit forces between driver and hub
	rotate around pivot point

The above functions were then transcribed into a further QFD2 Importance analysis to determine which components were most vital as per figure 12 below:

In future iterations of this form of analysis, components can be subjected to the same process as above to highlight critical factors in their manufacture that may influence desired outputs. This is used to reveal emergent behaviour and dependencies between components and can direct a designer to the most design-critical components and highlight the need for strict manufacturing tolerances, quality control etc in their manufacture.

